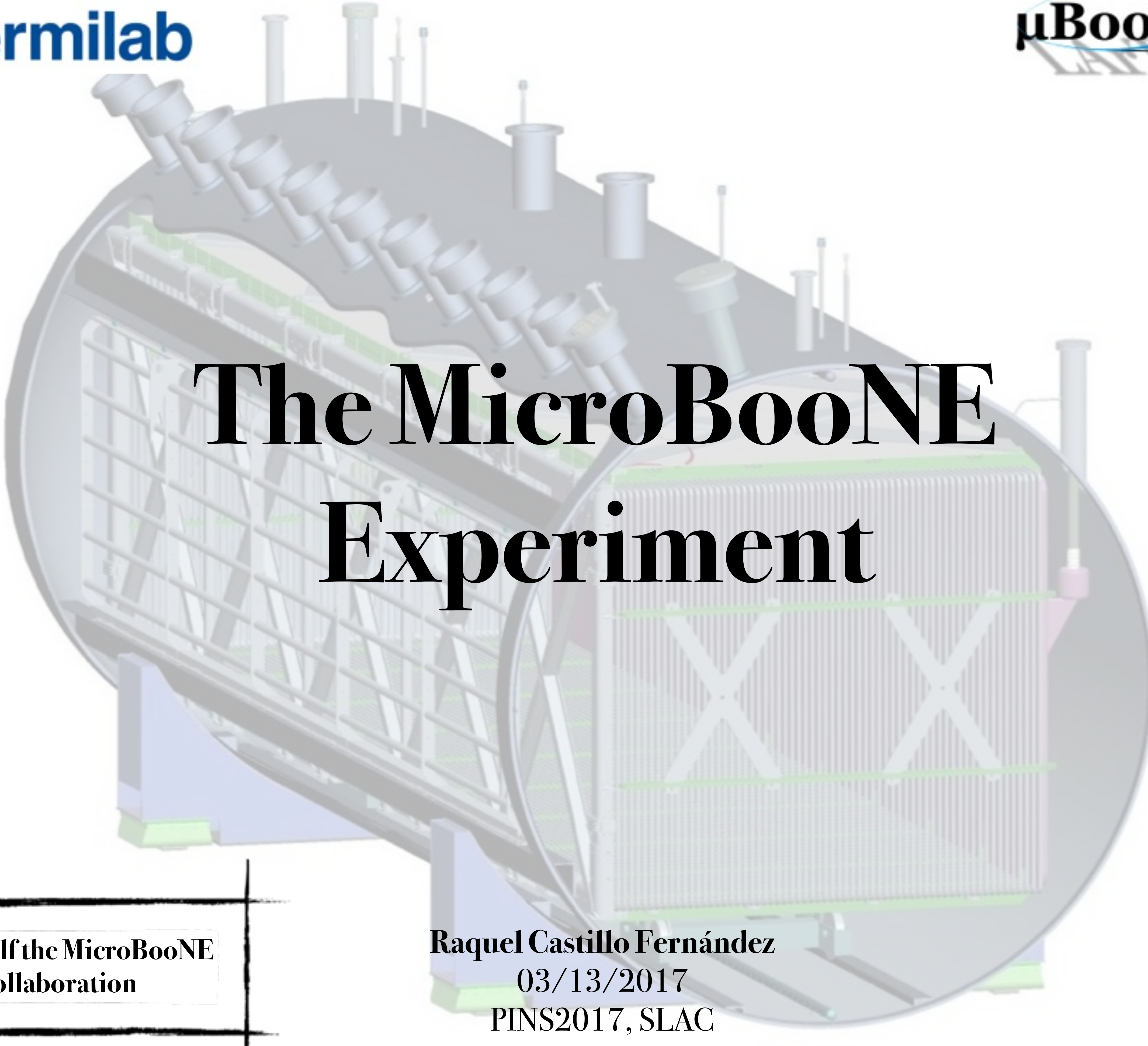


The MicroBooNE Experiment

On behalf the MicroBooNE collaboration

Raquel Castillo Fernández

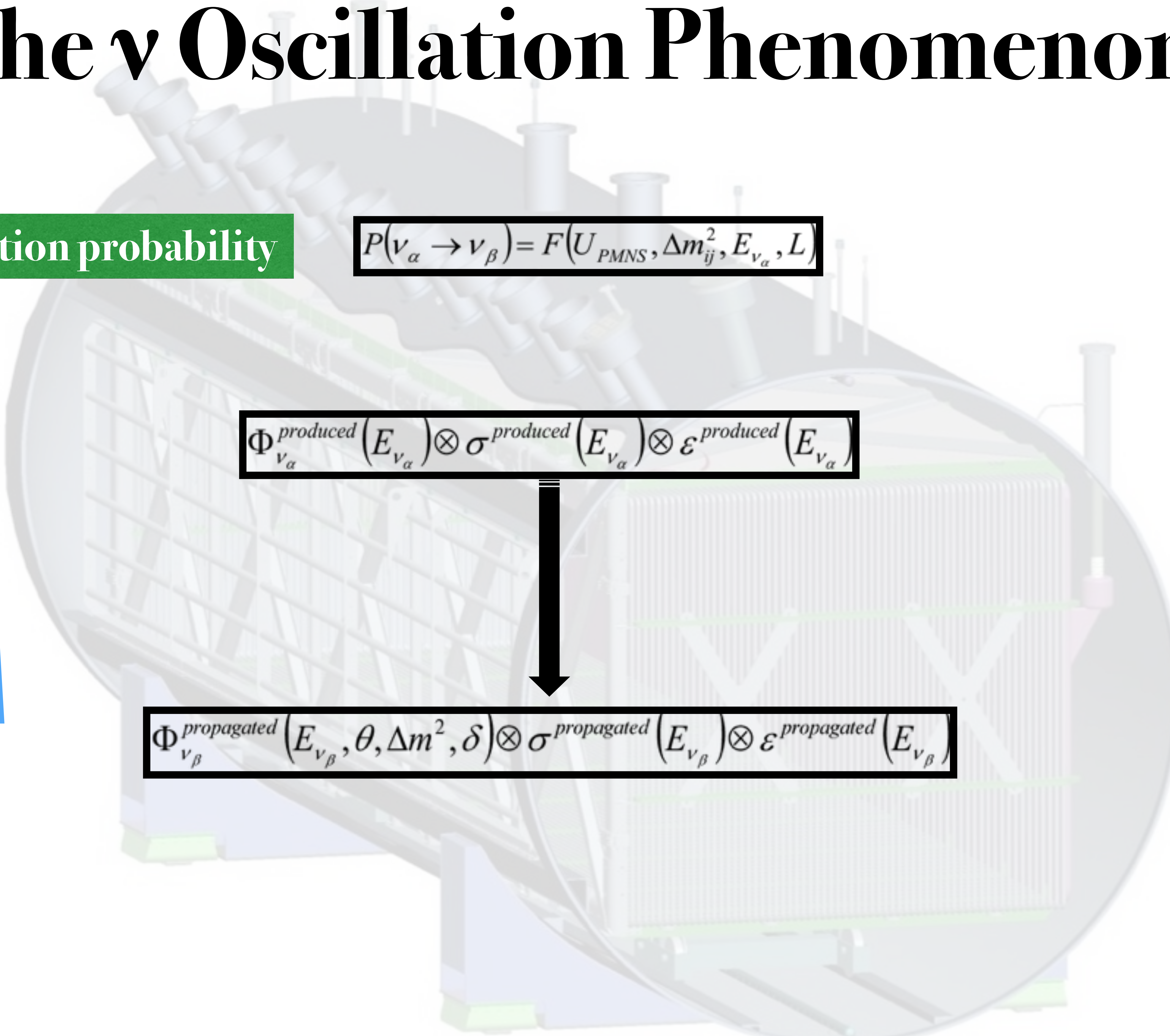
03/13/2017

PINS2017, SLAC

Outline

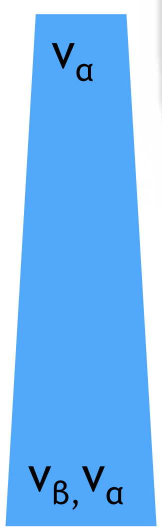
- **The ν Oscillation Phenomenon**
    - ν Energy Reconstruction
    - ν Interactions
- ν 'anomalies'
- Precision era: LArTPC
- The SBN Program
    - The MicroBooNE Detector
    - MicroBooNE ν Physics
    - MicroBooNE NuMI ν's

The ν Oscillation Phenomenon



Oscillation probability

$$\boxed{P(\nu_\alpha \to \nu_\beta) = F(U_{PMNS}, \Delta m^2_{ij}, E_{\nu_\alpha}, L)}$$



$$\boxed{\Phi^{produced}_{\nu_\alpha}(E_{\nu_\alpha}) \otimes \sigma^{produced}(E_{\nu_\alpha}) \otimes \varepsilon^{produced}(E_{\nu_\alpha})}$$

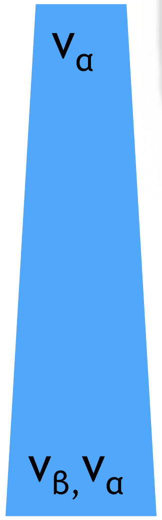
$$\Big\downarrow$$

$$\boxed{\Phi^{propagated}_{\nu_\beta}(E_{\nu_\beta}, \theta, \Delta m^2, \delta) \otimes \sigma^{propagated}(E_{\nu_\beta}) \otimes \varepsilon^{propagated}(E_{\nu_\beta})}$$

The ν Oscillation Phenomenon

Oscillation probability

$$P(\nu_\alpha \rightarrow \nu_\beta) = F(U_{PMNS}, \Delta m^2_{ij}, E_{\nu_\alpha}, L)$$



$$\Phi^{produced}_{\nu_\alpha}(E_{\nu_\alpha}) \otimes \sigma^{produced}(E_{\nu_\alpha}) \otimes \varepsilon^{produced}(E_{\nu_\alpha})$$

$$\Downarrow$$

$$\Phi^{propagated}_{\nu_\beta}(E_{\nu_\beta}, \theta, \Delta m^2, \delta) \otimes \sigma^{propagated}(E_{\nu_\beta}) \otimes \varepsilon^{propagated}(E_{\nu_\beta})$$

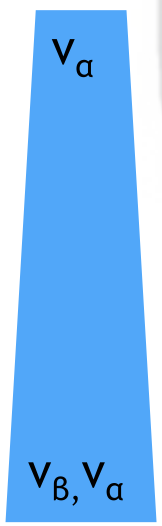
ν oscillations introduce differences in the flux spectrum and the ratio does not cancel the cross sections

$$\frac{N^{propagated}_{events}(E_\nu)}{N^{produced}_{events}(E_\nu)} = \frac{\int \sigma(E'_\nu)\Phi(E'_\nu)P(E_\nu|E'_\nu)P_{osc}(E'_\nu)dE'_\nu}{\int \sigma(E'_\nu)\Phi(E'_\nu)P(E_\nu|E'_\nu)dE'_\nu}$$

The ν Oscillation Phenomenon

Oscillation probability

$$P(\nu_\alpha \rightarrow \nu_\beta) = F(U_{PMNS}, \Delta m^2_{ij}, E_{\nu_\alpha}, L)$$



$$\Phi^{produced}_{\nu_\alpha}(E_{\nu_\alpha}) \otimes \sigma^{produced}(E_{\nu_\alpha}) \otimes \varepsilon^{produced}(E_{\nu_\alpha})$$

$$\Downarrow$$

$$\Phi^{propagated}_{\nu_\beta}(E_{\nu_\beta}, \theta, \Delta m^2, \delta) \otimes \sigma^{propagated}(E_{\nu_\beta}) \otimes \varepsilon^{propagated}(E_{\nu_\beta})$$

Main limitations:

- ν-Nucleus Interaction Cross Section
- Flux Uncertainties

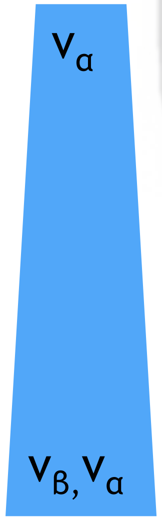
In general, the detector doesn't cover all the phase-space of generated neutrinos, and we may have un-predicted migrations along neutrino spectra.
Even if full phase-space is covered, cross section distributions for a non-oscillating hypothesis are still not fully understood.

One detector scenario

The ν Oscillation Phenomenon

Oscillation probability

$$P(\nu_\alpha \rightarrow \nu_\beta) = F(U_{PMNS}, \Delta m_{ij}^2, E_{\nu_\alpha}, L)$$



$$\Phi_{\nu_\alpha}^{produced}(E_{\nu_\alpha}) \otimes \sigma^{produced}(E_{\nu_\alpha}) \otimes \varepsilon^{produced}(E_{\nu_\alpha})$$

$$\Downarrow$$

$$\Phi_{\nu_\beta}^{propagated}(E_{\nu_\beta}, \theta, \Delta m^2, \delta) \otimes \sigma^{propagated}(E_{\nu_\beta}) \otimes \varepsilon^{propagated}(E_{\nu_\beta})$$

Main limitations:

- ν-Nucleus Interaction Cross Section
- Flux Uncertainties

With 2 detectors, the near one can be used to understand neutrino-nucleus interaction effects. However, even if the 2 detectors use the same target, since neutrino energy spectra is not the same, we cannot cancel cross section uncertainties.

Two/more detector scenario

ν Energy Reconstruction

Since we don't have a monochromatic ν beam we deal with the ν energy reconstruction:

- E_ν relies on lepton kinematics
  - Different methods, relying on the reaction type description or final state particles
- Either if we use an exclusive or inclusive channel in the measurement,
  - hadron composition and its kinematics are strongly affected by FSI
- Fermi momentum, Pauli blocking and bound energy plays significant role
- Neutrons are not typically accessible by current ν detectors.

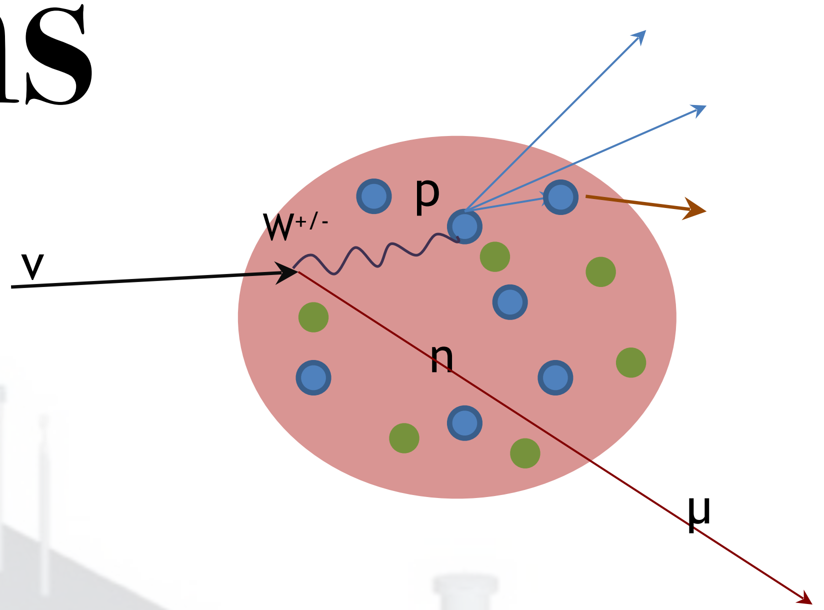
Some experiments (i.e. ν_e appearance @T2K) use only lepton kinematics in the oscillation fit to reduce un-knows.

But still, even if this reduces the extrapolation, lepton kinematics are not yet fully understood.

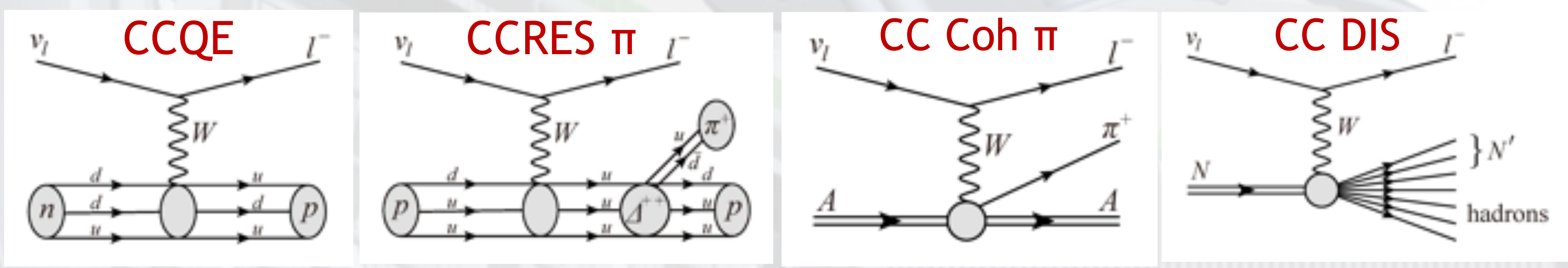
Because life is not easy…

ν Interactions

To characterize the un-oscillated neutrinos we use CC events



Interaction **neutrino-nucleon**



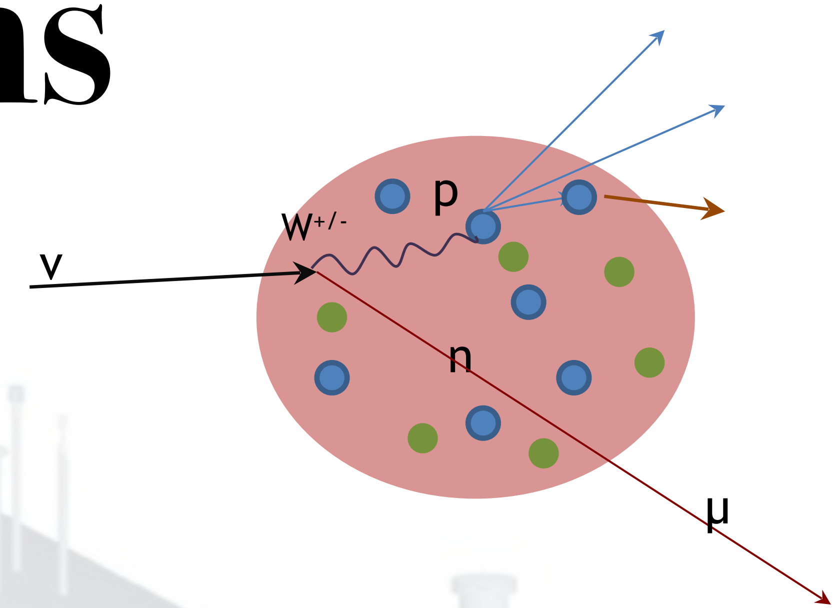
Interaction with the **nucleus**

- **F**inal **S**tate **I**nteraction:
  - Pion absorption
  - Proton,pion scattering
  - **Ch**arge **ex**-change
- Nuclear **S**hort-**R**ange **E**ffects
  - **M**eson **E**x-change **C**urrent
- Nuclear **L**ong-**R**ange **E**ffects
- Nuclear Modelling
  - Fermi motion
  - Binding energy
  - Pauli blocking

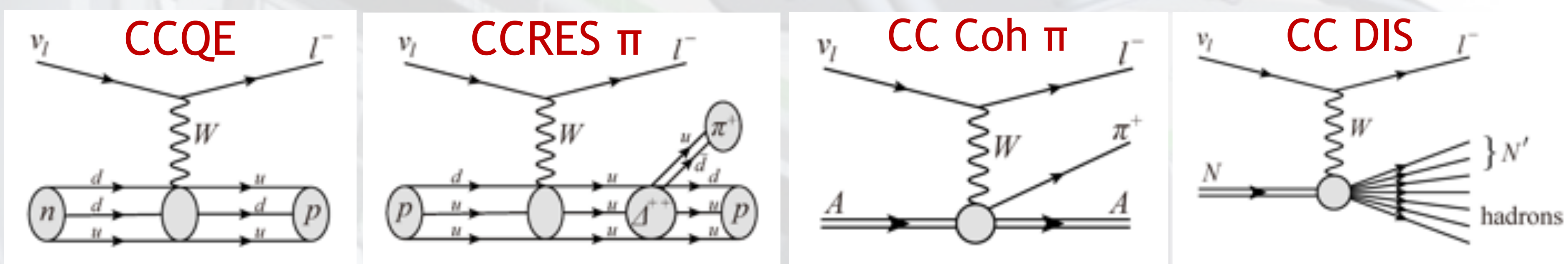
Because life is not easy…

ν Interactions

To characterize the un-oscillated neutrinos we use CC events



Interaction neutrino-nucleon



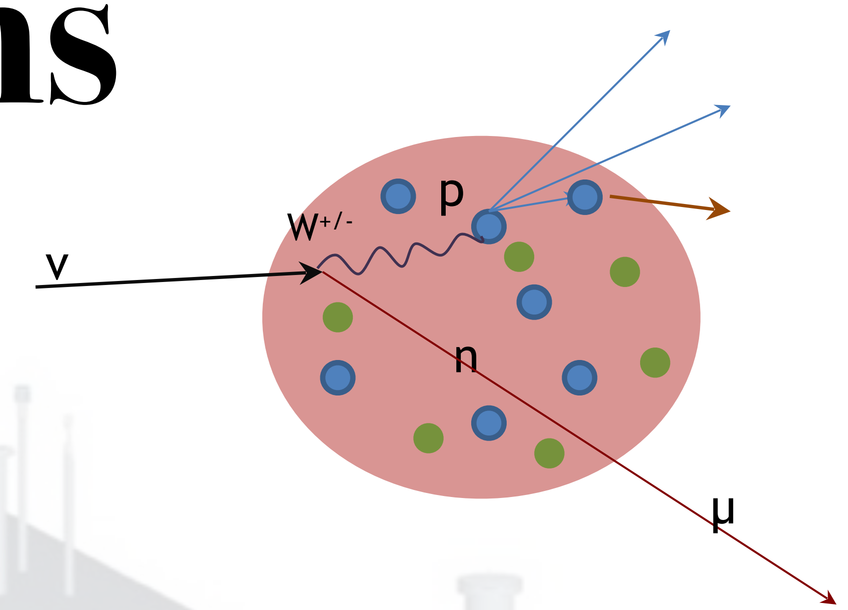
Interaction with the nucleus

- Final State Interaction:
  - Pion absorption
  - Proton,pion scattering
  - Charge ex-change
- Nuclear Short-Range Effects
  - Meson Ex-change Current
- Nuclear Long-Range Effects
- Nuclear Modelling
  - Fermi motion
  - Binding energy
  - Pauli blocking
- ν_e/ν_μ

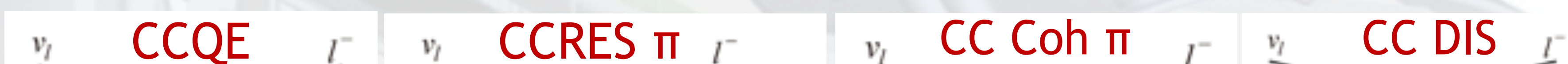
Because life is not easy…

ν Interactions

To characterize the un-oscillated neutrinos we use CC events



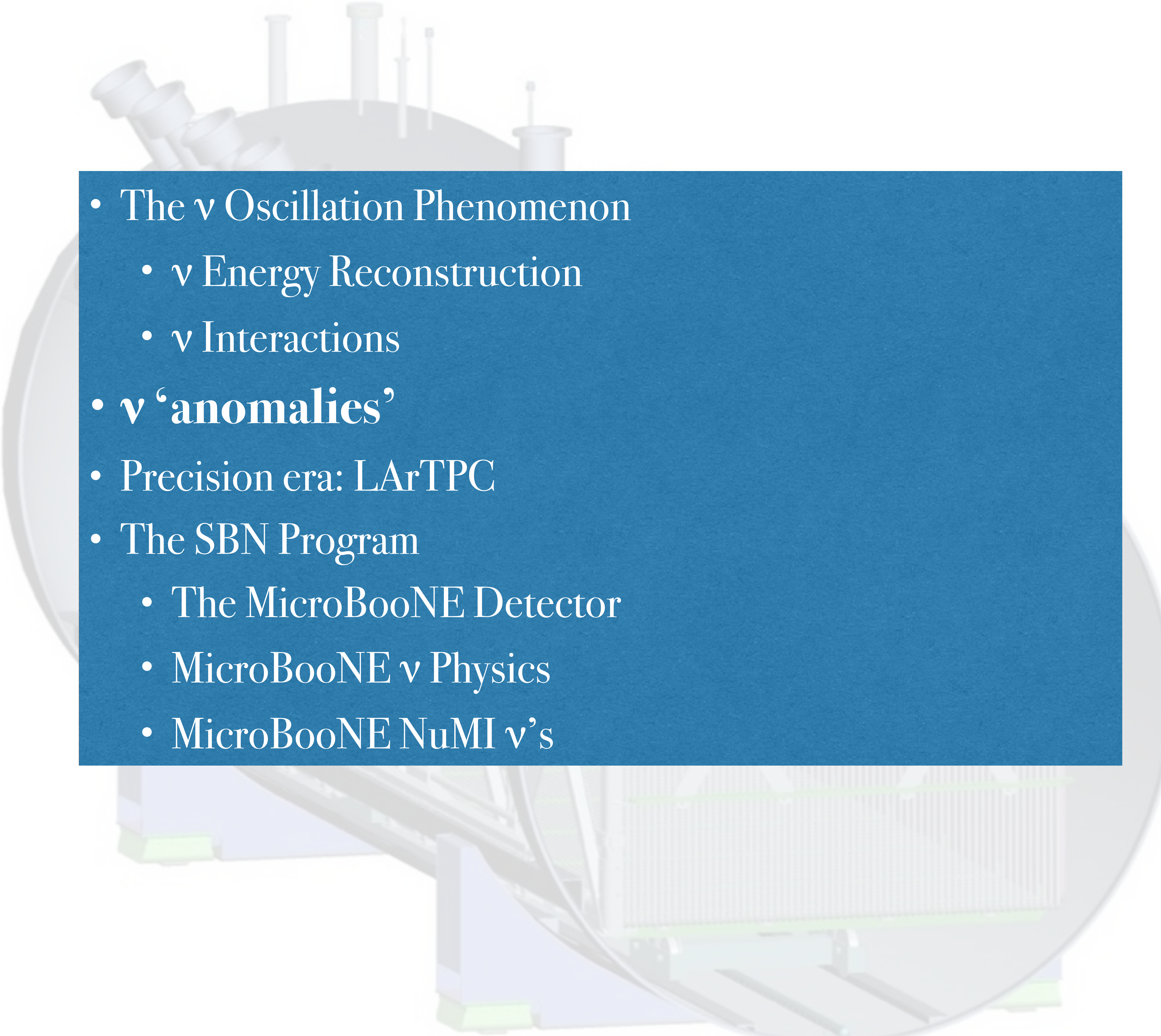
Interaction neutrino-nucleon



Known limitations for neutrino-carbon/water experiments (T2K, NOvA, MiniBooNE) in osc. analysis.

For argon we expect most of these effects to be bigger

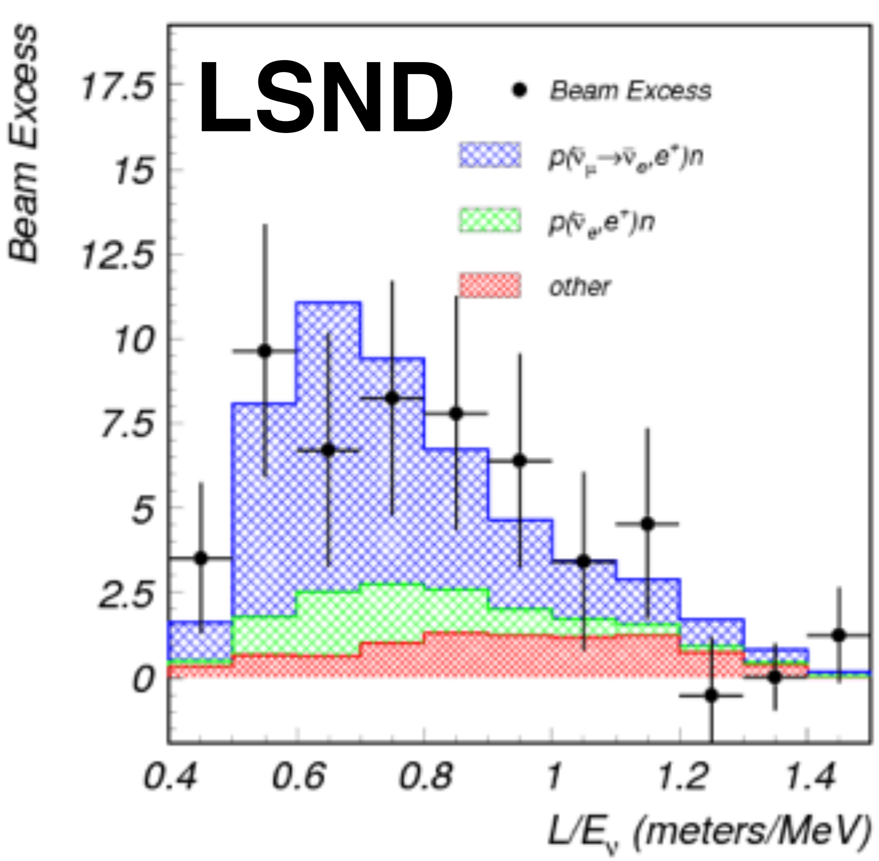
- Final State Interaction:
  - Pion absorption
  - Proton, pion scattering
  - Charge ex-change
- Nuclear Short-Range Effects
  - Meson Ex-change Current
- Nuclear Long-Range Effects
- Nuclear Modelling
  - Fermi motion
  - Binding energy
  - Pauli blocking
- ν_e/ν_μ



- The ν Oscillation Phenomenon
  - ν Energy Reconstruction
  - ν Interactions
- **ν ‘anomalies’**
- Precision era: LArTPC
- The SBN Program
  - The MicroBooNE Detector
  - MicroBooNE ν Physics
  - MicroBooNE NuMI ν’s

ν ‘anomalies’

In addition to all… do we have only 3 neutrino families?
Within the Standard Model we have measured 3 families.
…and in the meanwhile, <u>experiments observe unpredicted events</u>…



Phys.Rev. D64 (2001) 112007

$\bar{\nu}_\mu \rightarrow \bar{\nu}_e$?

Non-interacting neutrinos? (i.e. sterile)

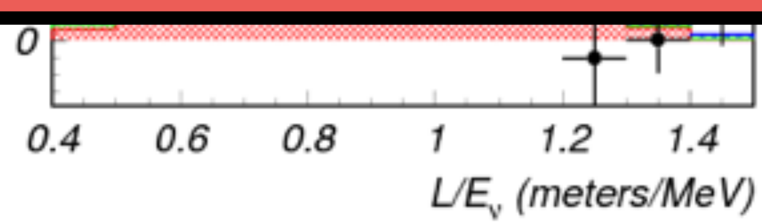
Need to see similar effect in neutrino mode to discard CP and ν_μ to discard lepton flavor differences.

ν ‘anomalies’

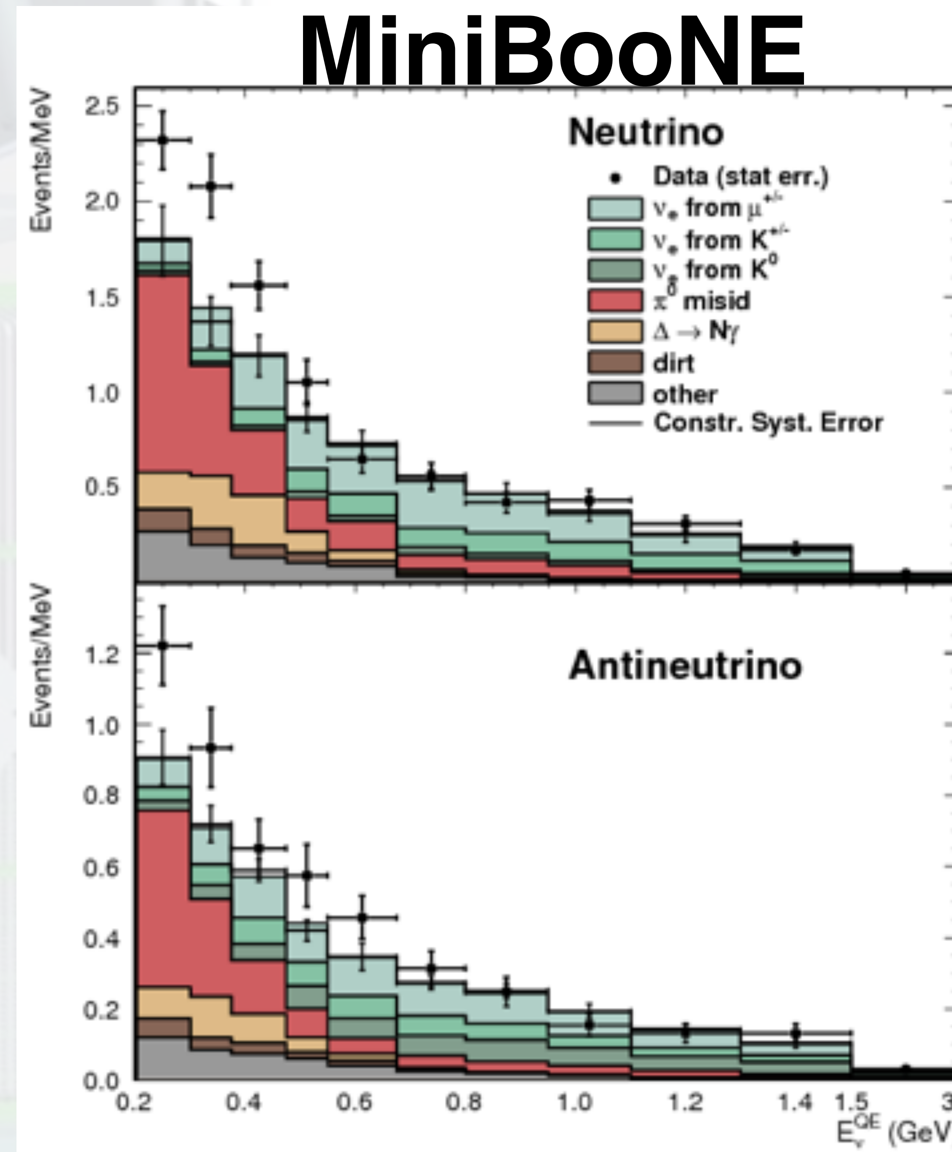
In addition to all… do we have only 3 neutrino families?
Within the Standard Model we have measured 3 families.
…and in the meanwhile, <u>experiments observe unpredicted events</u>…

To identify origin of the low energy events we need <u>higher phase-space coverage & reduced background</u>:

- Identify e^-/γ
  - Crucial to reduce background
- Lower energetic particles should be accessible



Phys.Rev. D64 (2001) 112007



Phys.Rev.Lett. 110 (2013) 161801

ν ‘anomalies’

Up to now, MiniBooNE data/MC discrepancies:

Pion production uncertainties
ν induced π^0 production underestimations, observed in other experiments (e.g. MINERνA)

More ν-nucleus scattering un-knows?

More exotic physics (i.e. heavy ν)

Sterile neutrino(s): 3+1, 3+2, 3+3 scenarios

Clear identification of $e^{-/+}/\gamma$ events

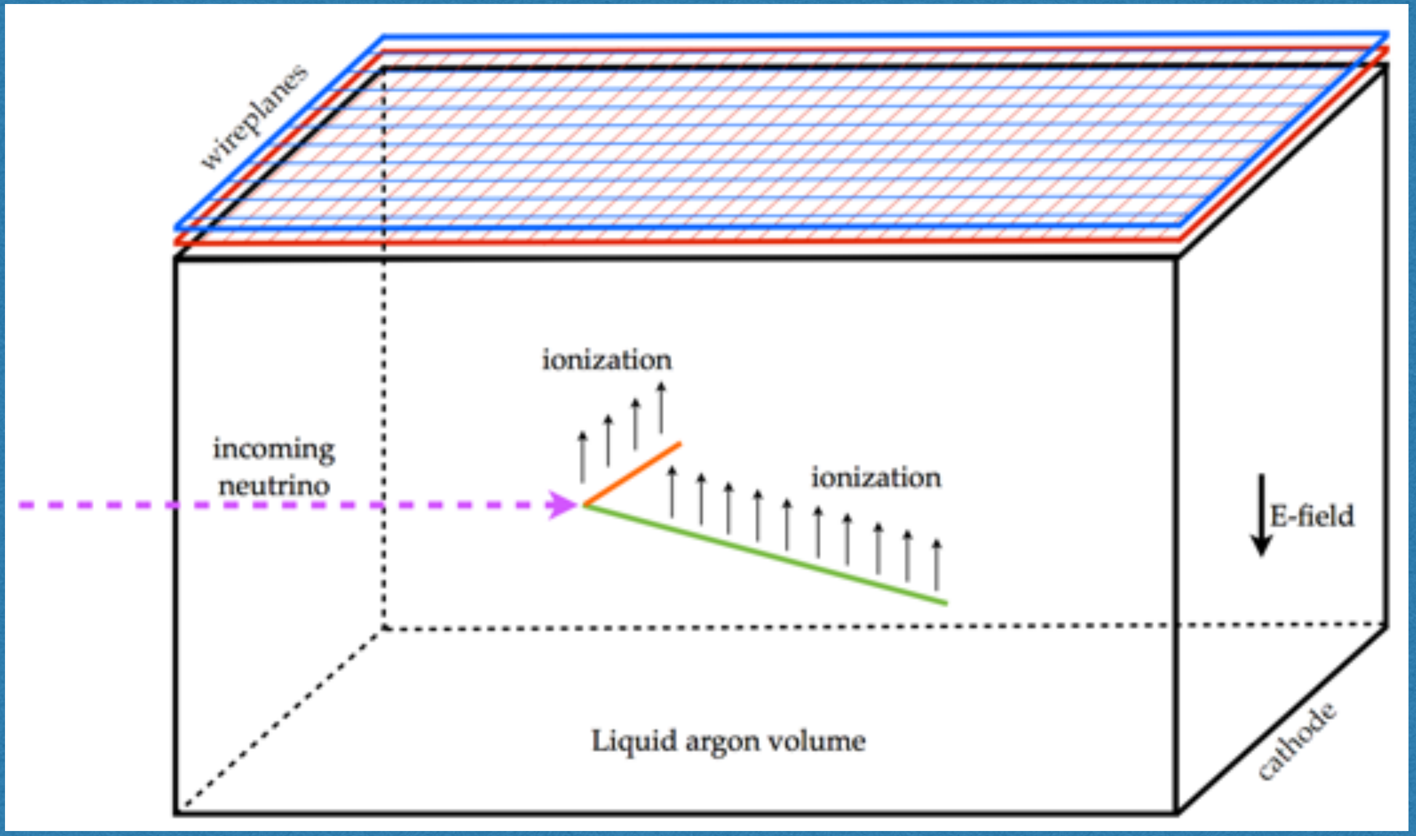
Understand differences ν_e-ν_μ

Better model constraints in ν-nucleus scattering

- The ν Oscillation Phenomenon
    - ν Energy Reconstruction
    - ν Interactions
- ν ‘anomalies’
- **Precision era: LArTPC**
- The SBN Program
    - The MicroBooNE Detector
    - MicroBooNE ν Physics
    - MicroBooNE NuMI ν’s

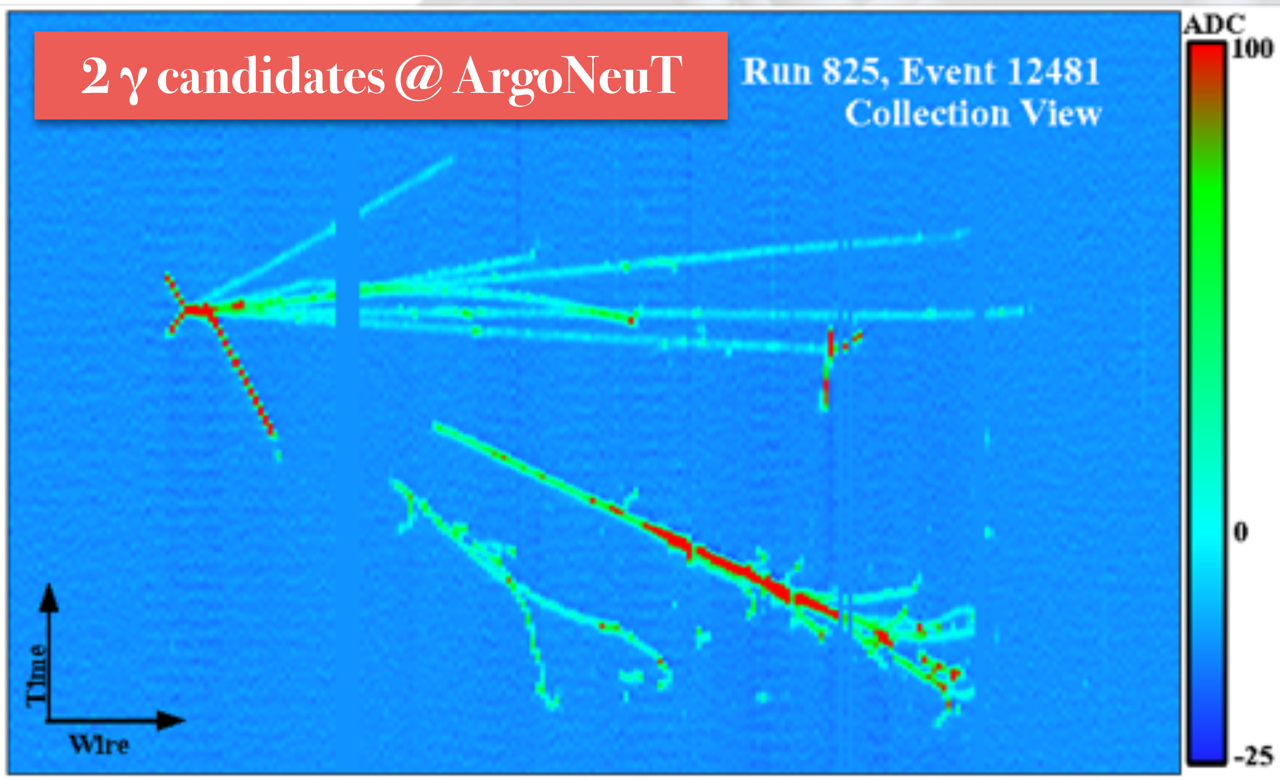
Precision era: Liquid Argon TPC

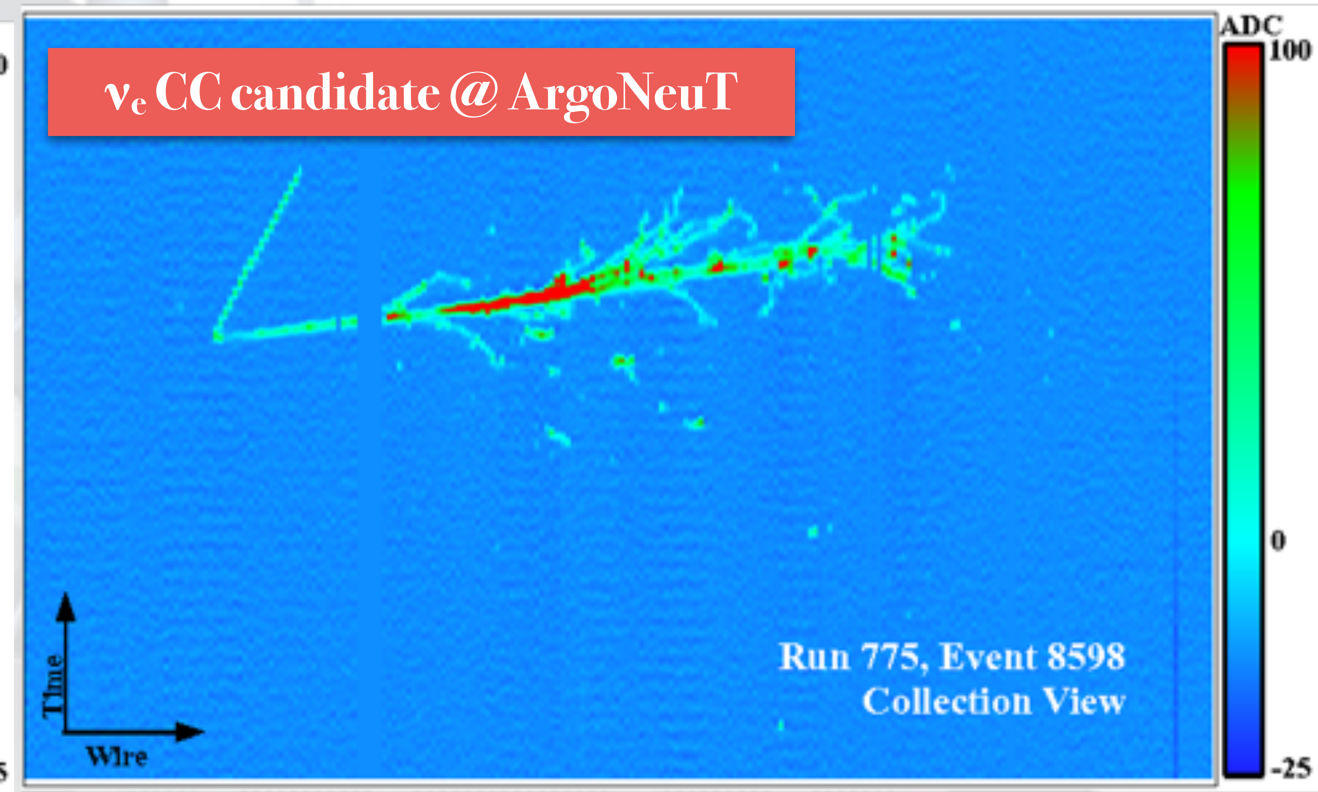
- Ionization from traversing charged particles is drifted along E-field to the segmented wire planes.
  - argon ionizes easily, ~70 ke/cm (@500 V/cm)
- Wire pulse timing information is combined with known drift speed to determine drift-direction coordinate.
- Calorimetry information is extracted from wire pulse characteristics.
- Abundant **scintillation light**, which LAr is transparent to, also available for collection and triggering.
  - **40k γ/MeV @null E-field**
- Argon is **40%** more dense than water.
- **1%** abundance in the atmosphere.

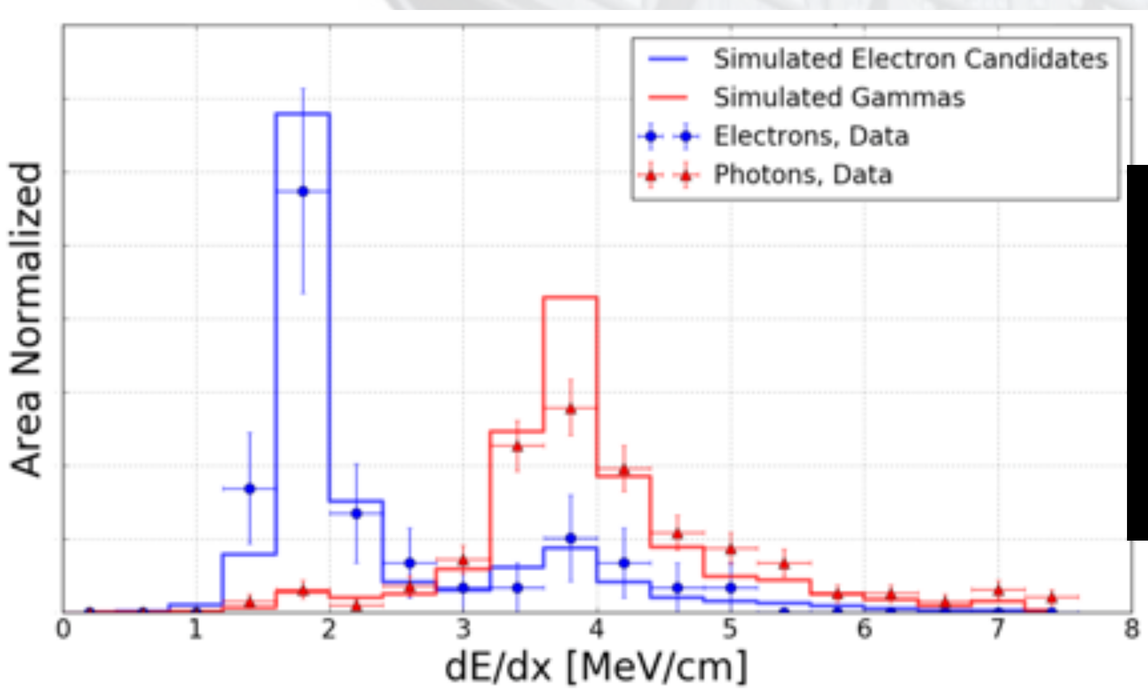


Precision era: Liquid Argon TPC

Phys.Rev.D arXiv:1610.04102

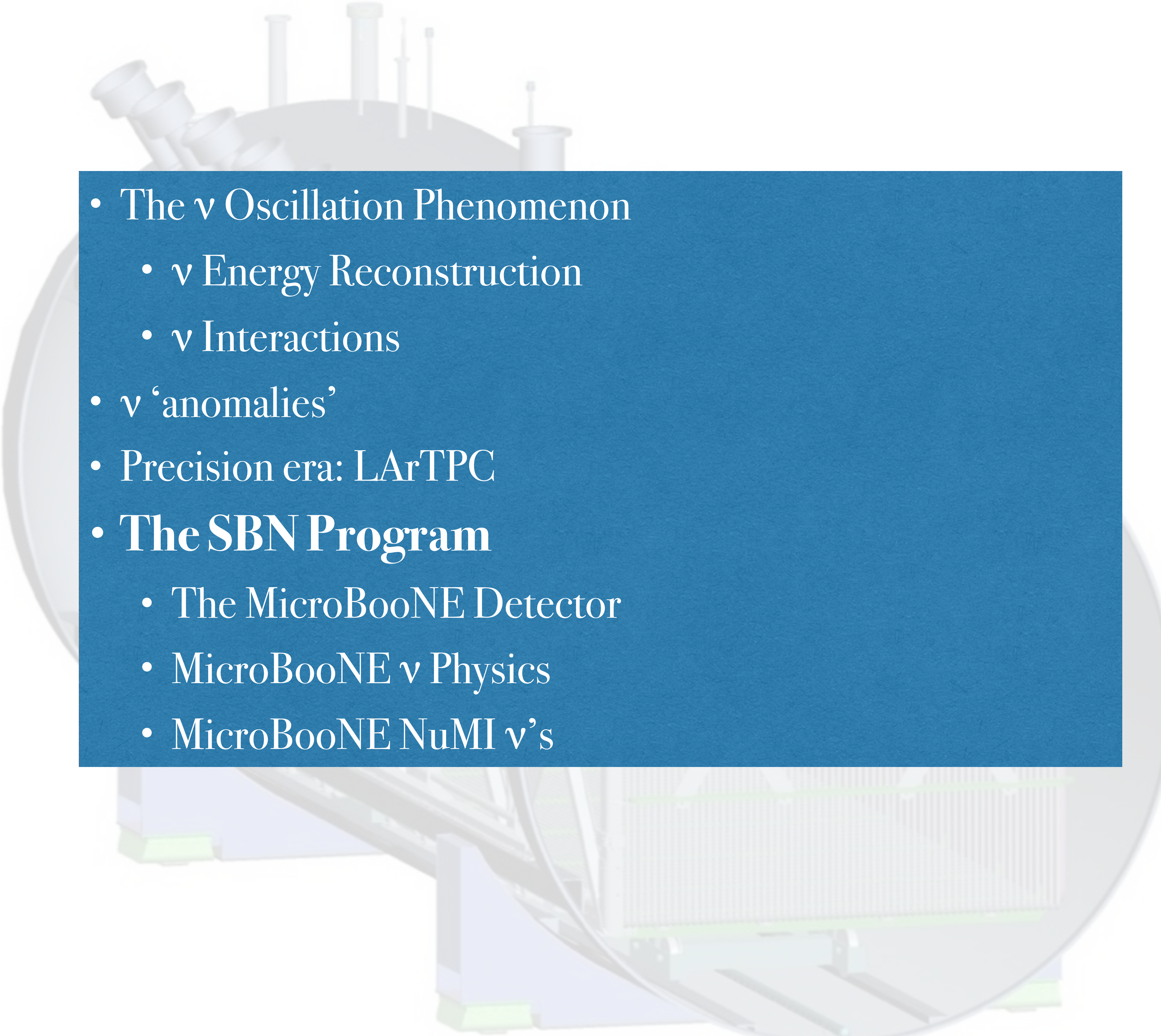






Ability to identify particles at any direction from @20MeV

Distinguishable signature e^-/γ



- The ν Oscillation Phenomenon
  - ν Energy Reconstruction
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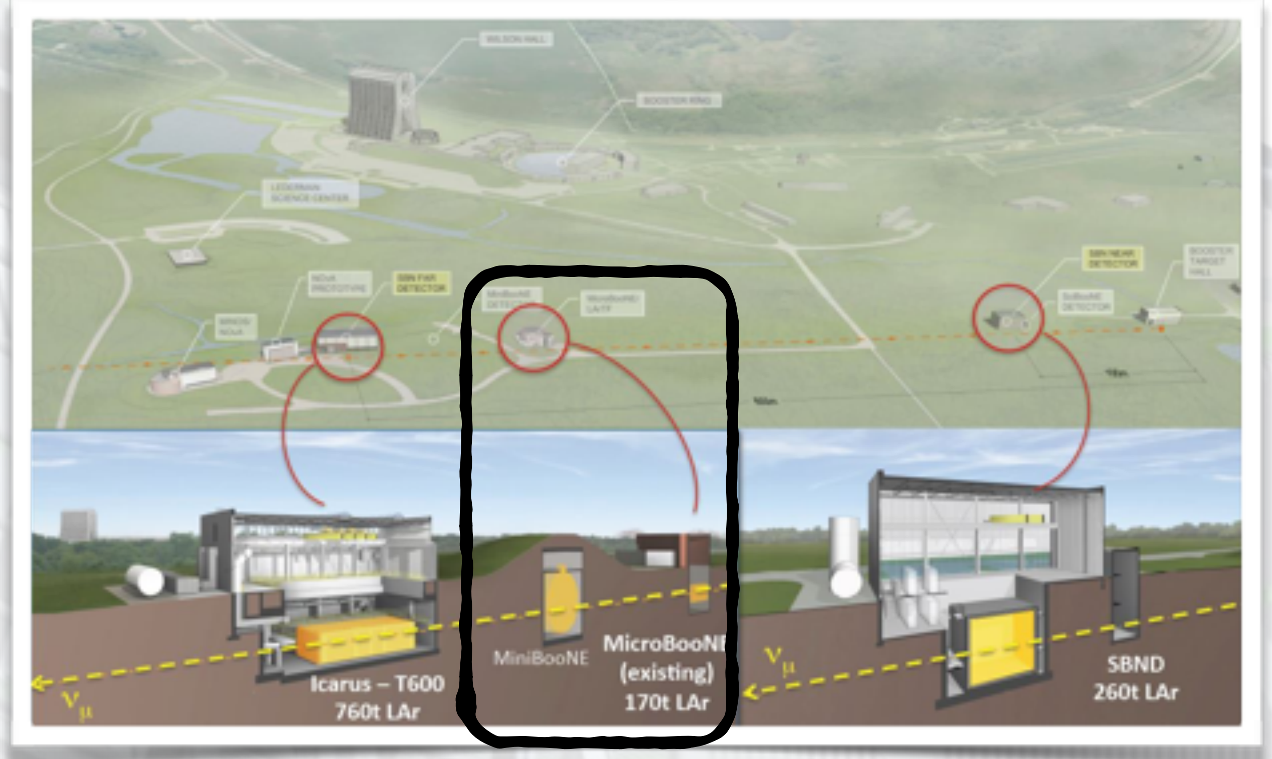
  - MicroBooNE NuMI ν’s

The SBN Program

SBN (Short Baseline Neutrino) aims to search for non-standard ν oscillations by ν_e appearance and ν_μ disappearance with unprecedented precision in BNB.



Main MicroBooNE physics goals:

- Investigate MiniBooNE low- energy un-predicted data (ν_e CC events)
- Measure first low-energy ν-Ar cross sections
- R&D for Deep Underground Neutrino Experiment (DUNE)
- Joint oscillation analysis within the Short Baseline Neutrino (SBN) program

+ Exotic physics capability studies (proton decay, SN,..). See Yun-Tse's talk this Thursday!

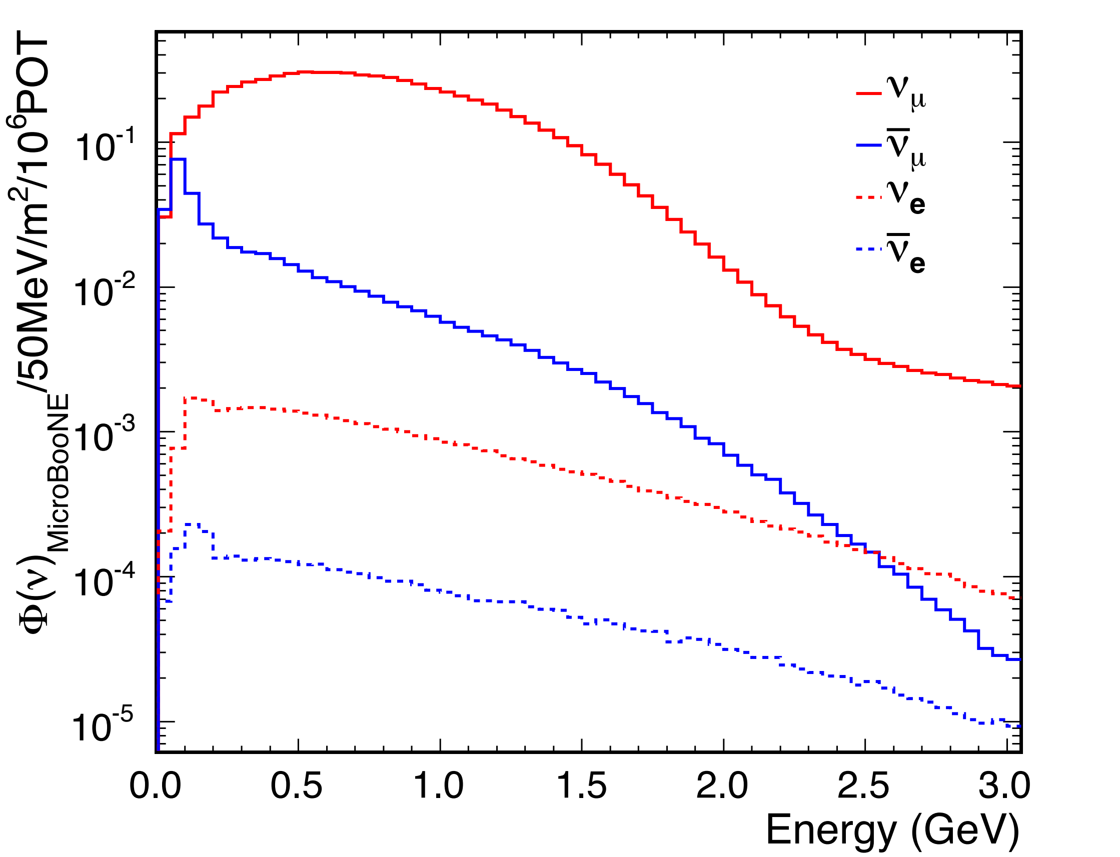
The BNB ν beam

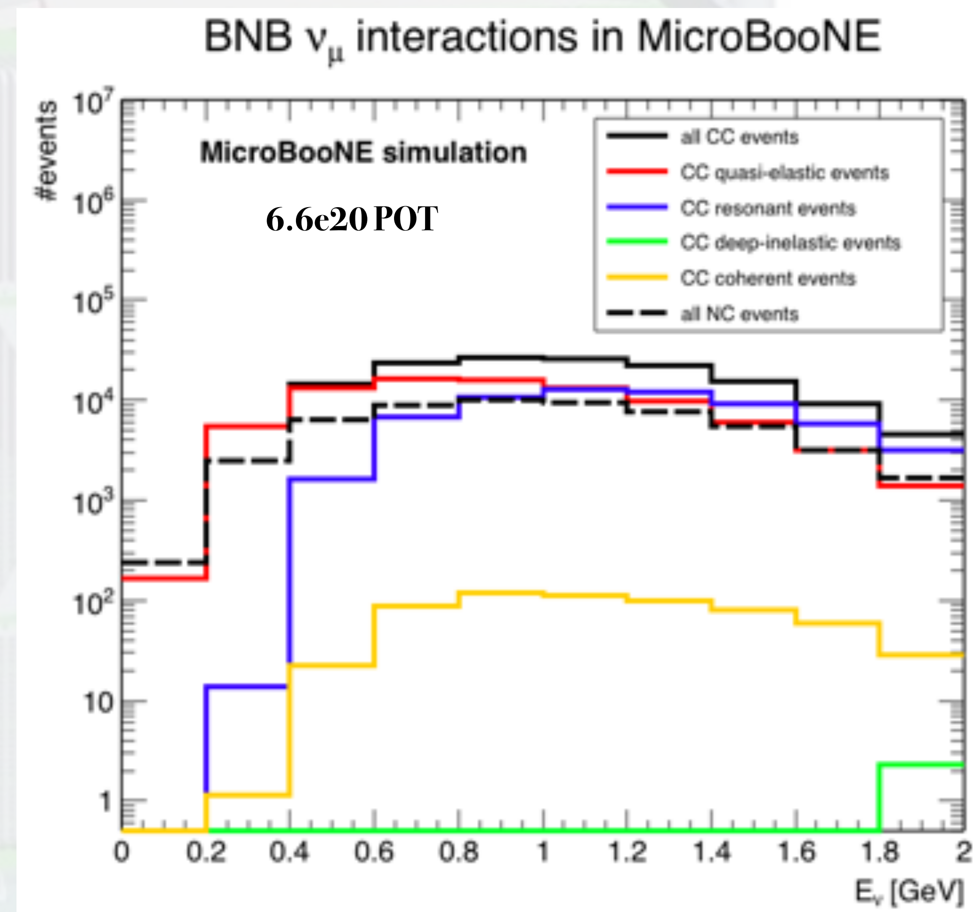
8 GeV Protons from BNB

Almost pure ν_μ beam (0.5% intrinsic ν_e contamination)

Located on-axis from ν source @470m

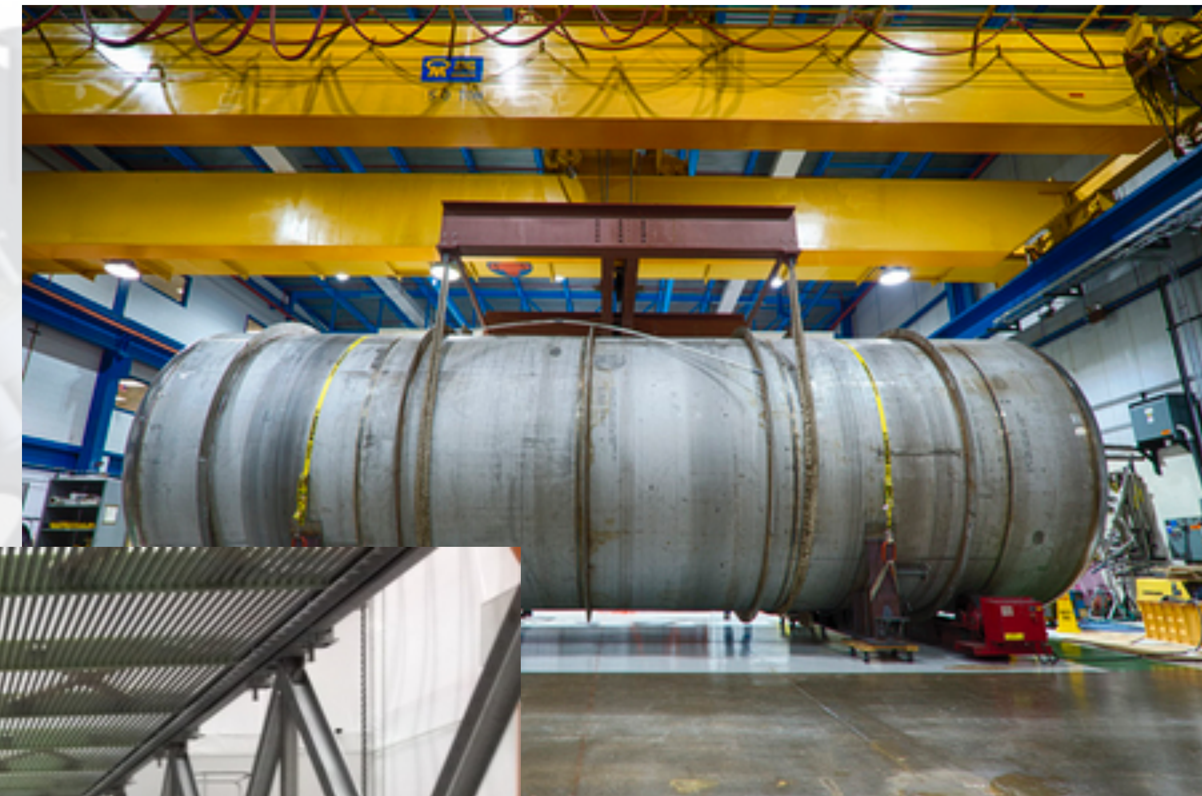
Booster Neutrino Beam (BNB) flux at MicroBooNE

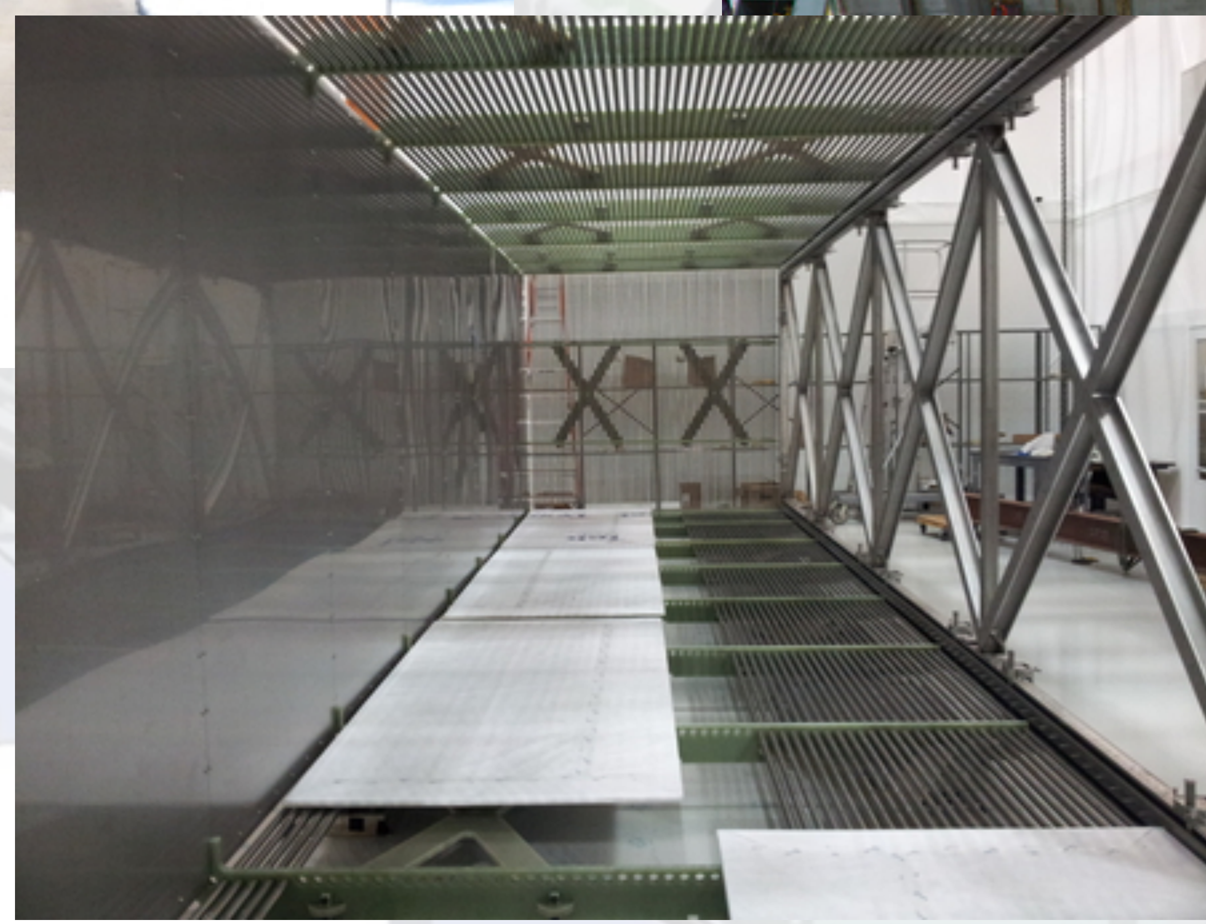




The MicroBooNE Detector

MicroBooster Neutrino Experiment



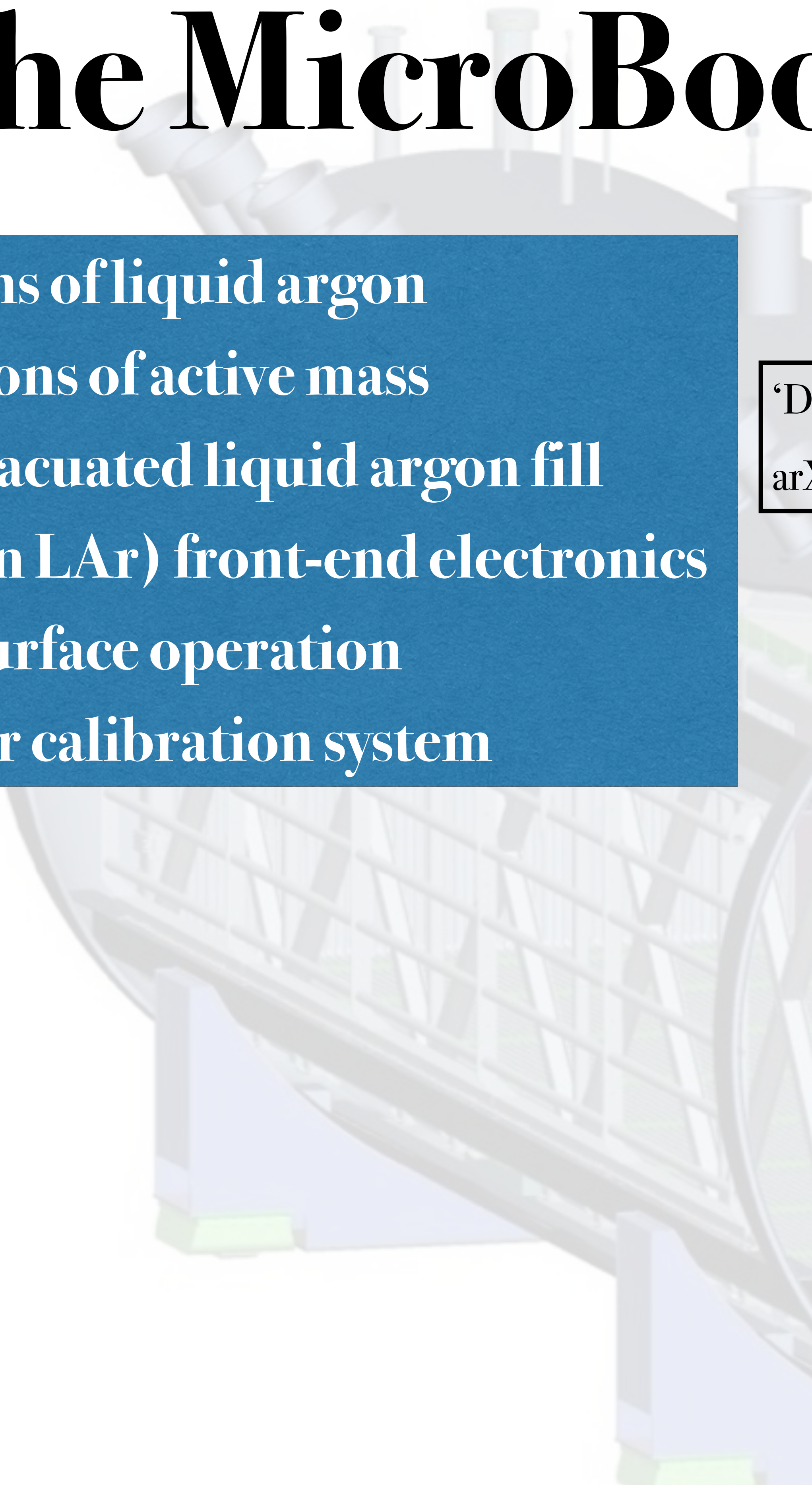


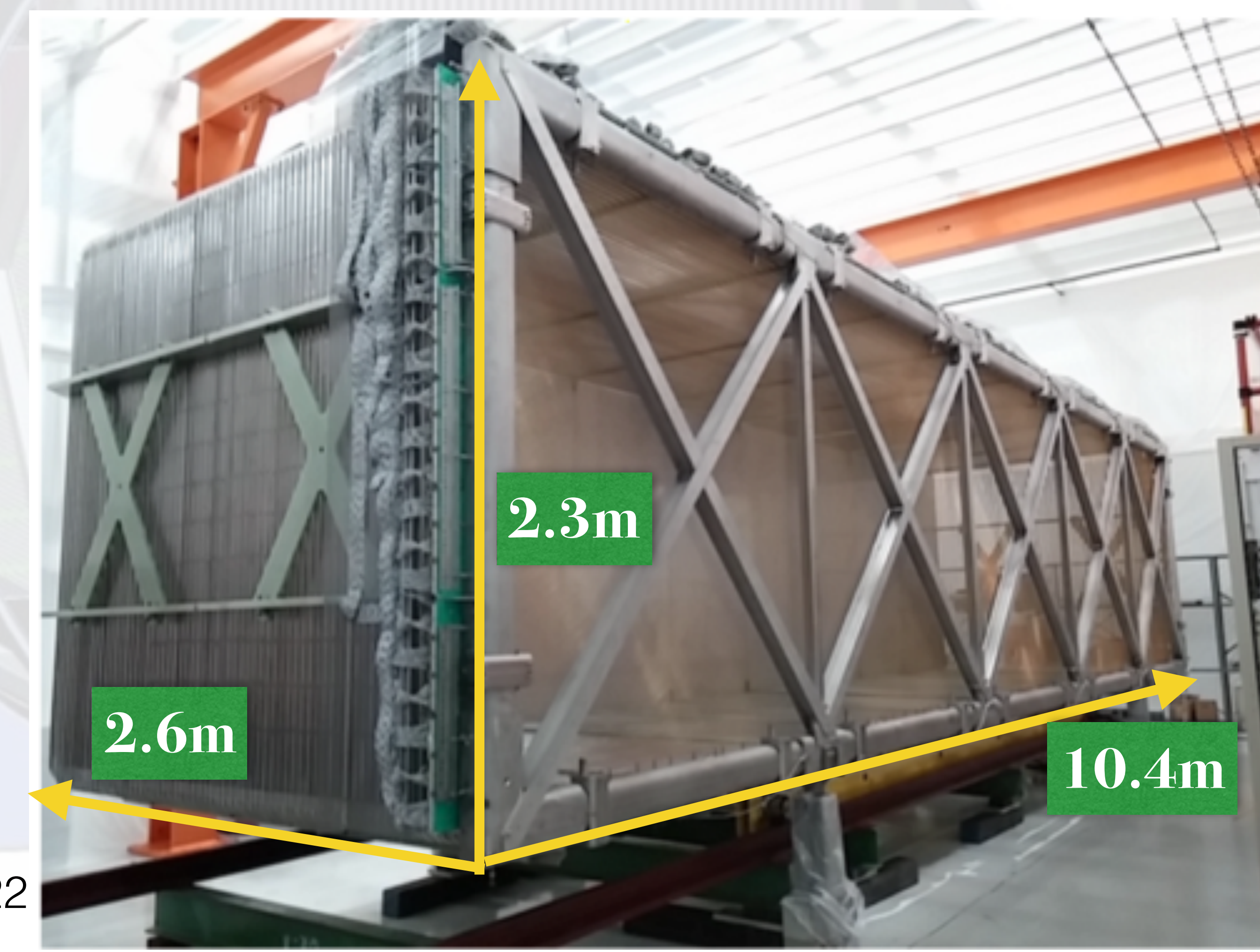
156 collaborators from 28 institutions (7 non-U.S.)

The MicroBooNE Detector

- 170 tons of liquid argon
  - 86 tons of active mass
- Non-evacuated liquid argon fill
- Cold (in LAr) front-end electronics
- Near-surface operation
- UV laser calibration system

'Design and Construction of the MicroBooNE Detector'
arXiv:1612.05824

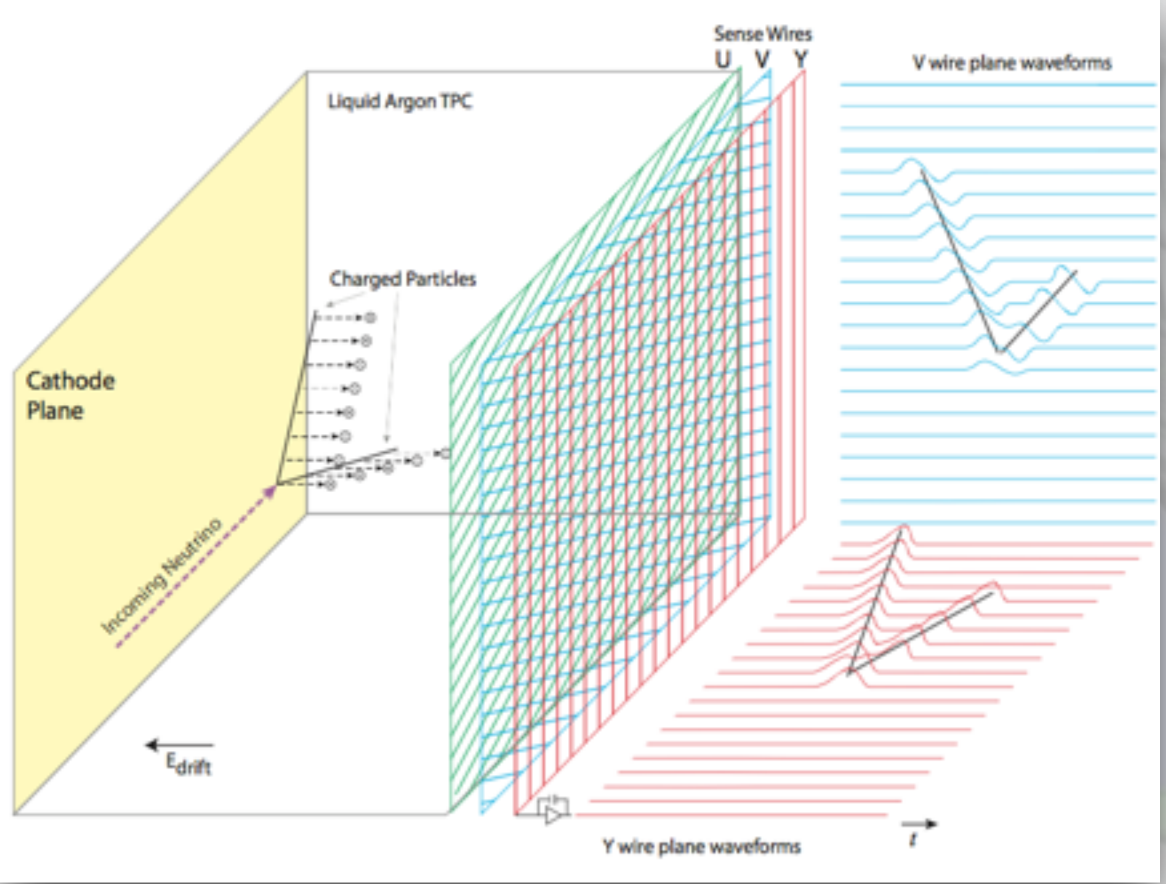




MicroBooNE TPC

- 8192 wires, 3mm separation between wires
- Two induction planes (U, V) and one collection plane (Y), 3 mm pitch
  - signal on all three planes
  - Drift E-field at 273 V/cm, surrounding field cage allows E-field uniformity
  - 8000+ channels with front-end electronics in LAr
- <u>3D event reconstruction</u> by combining signals from all 3 planes (2 required)

arXiv:1609.06169 [physics.ins-det]



First large scale LArTPC to employ cold front end electronics

- Suppresses noise

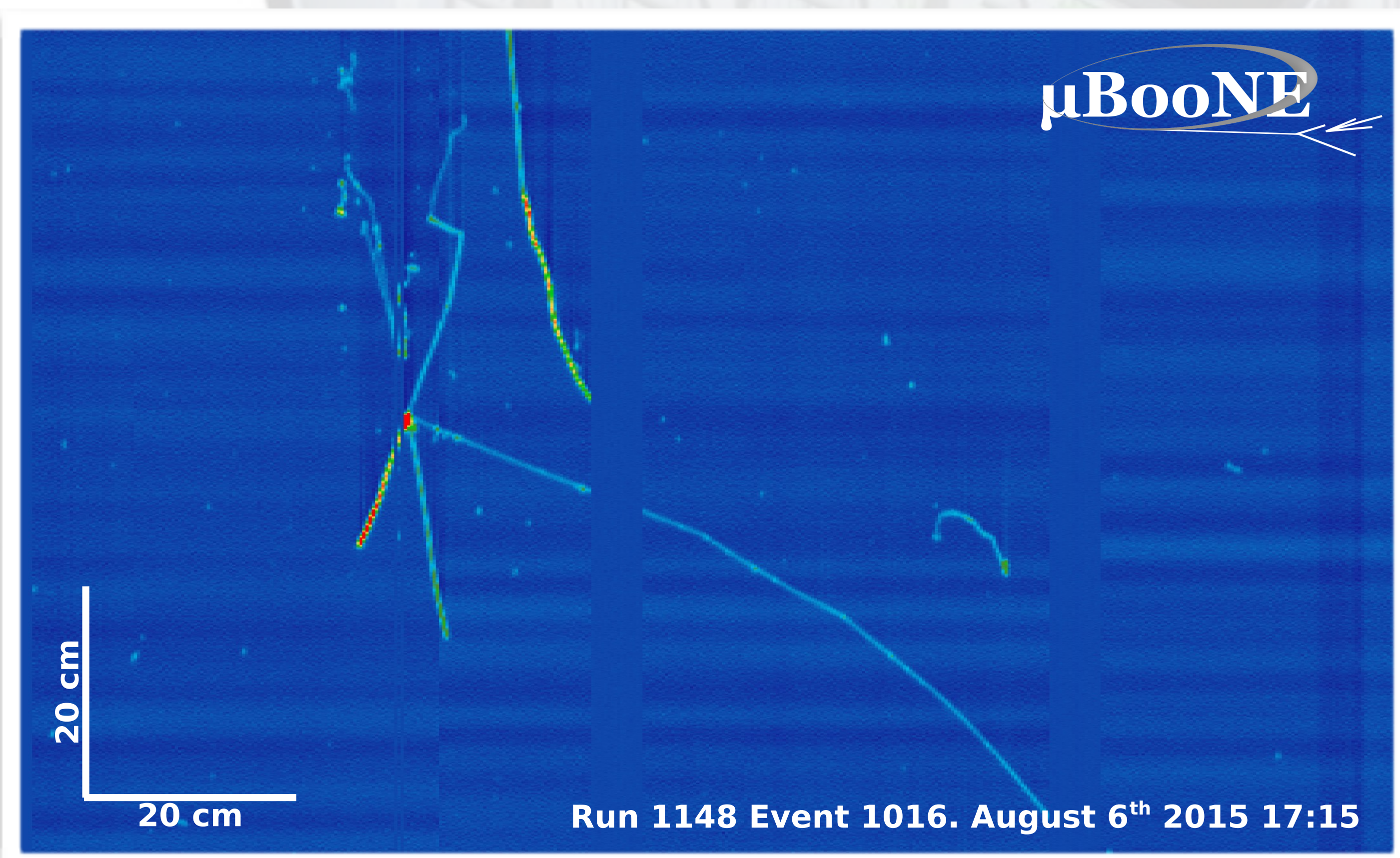
RMS noise on the readout wires drops as the cryostat is cooled

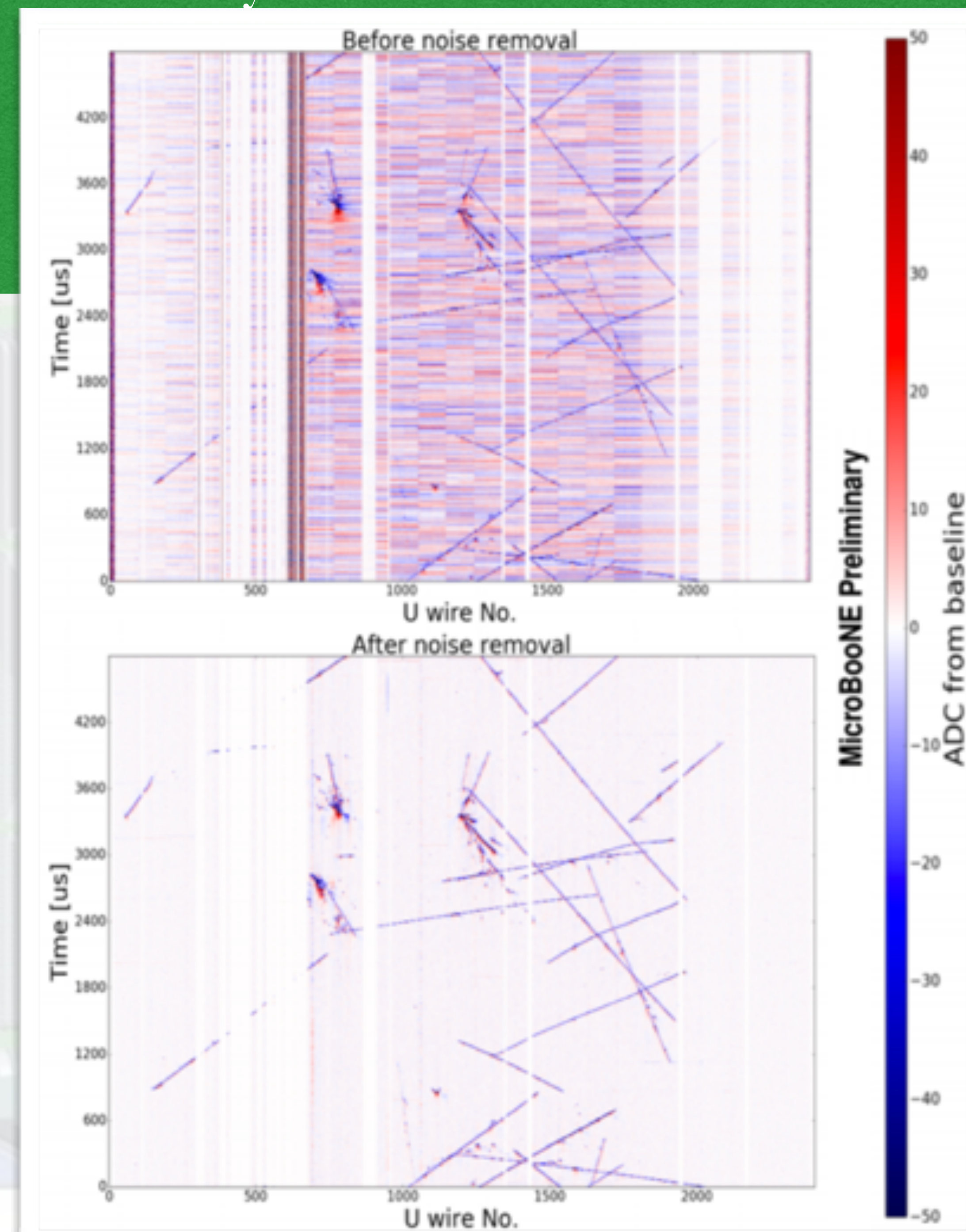
- The noise begins to raise once LAr is added due to change in capacitance

MicroBooNE TPC

MICROBOONE-NOTE-1016-PUB

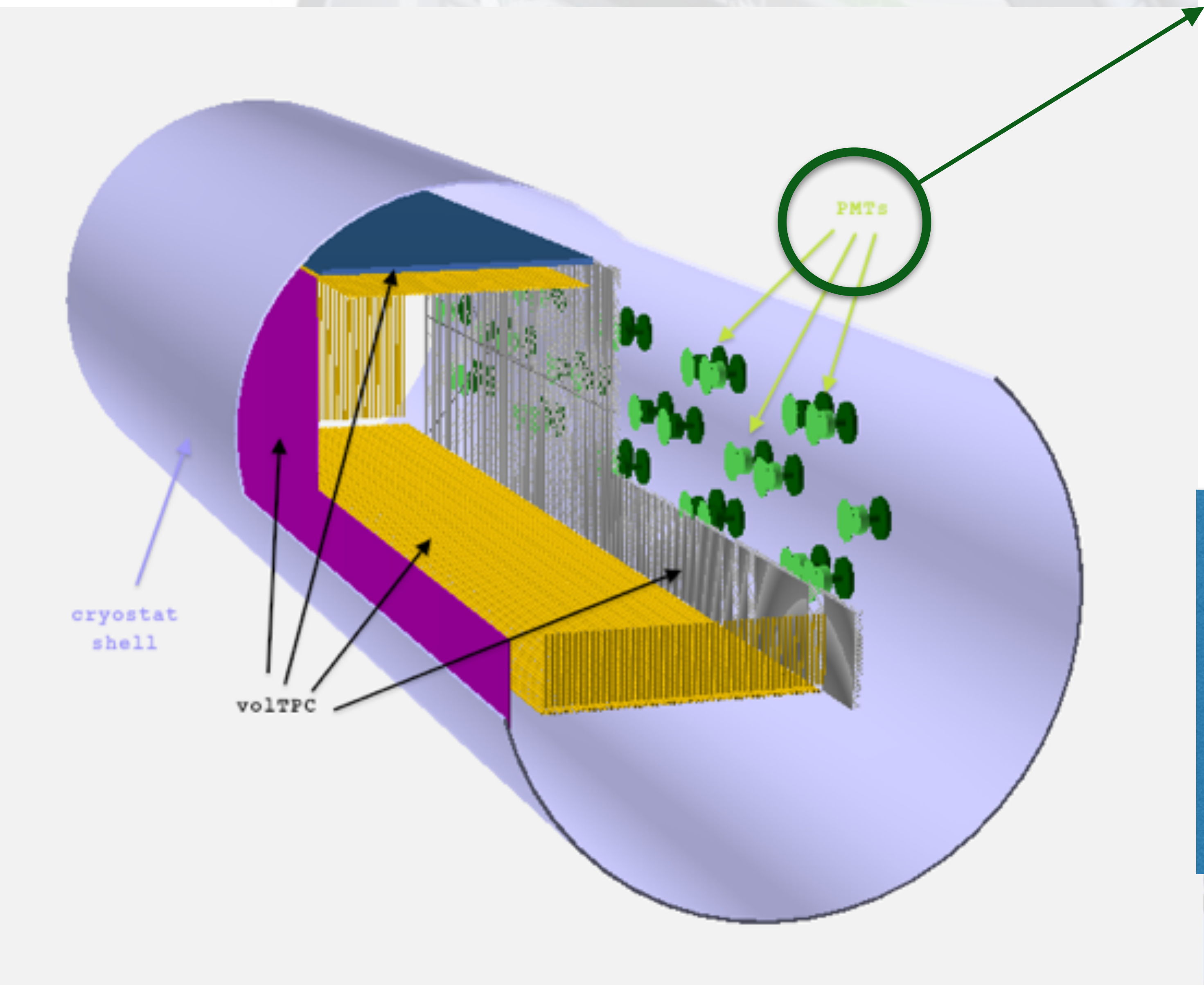
- Coherent noise over group of channels
  - This noise is associated to a voltage regulator on a warm service board
  - With software filtering we are able to improve signal-to-noise by factor of 2
- Signal-to-noise ratio after software noise filtering
- U plane 15.8 : 1
- V plane 12.9 : 1
- Y plane 45.3 : 1



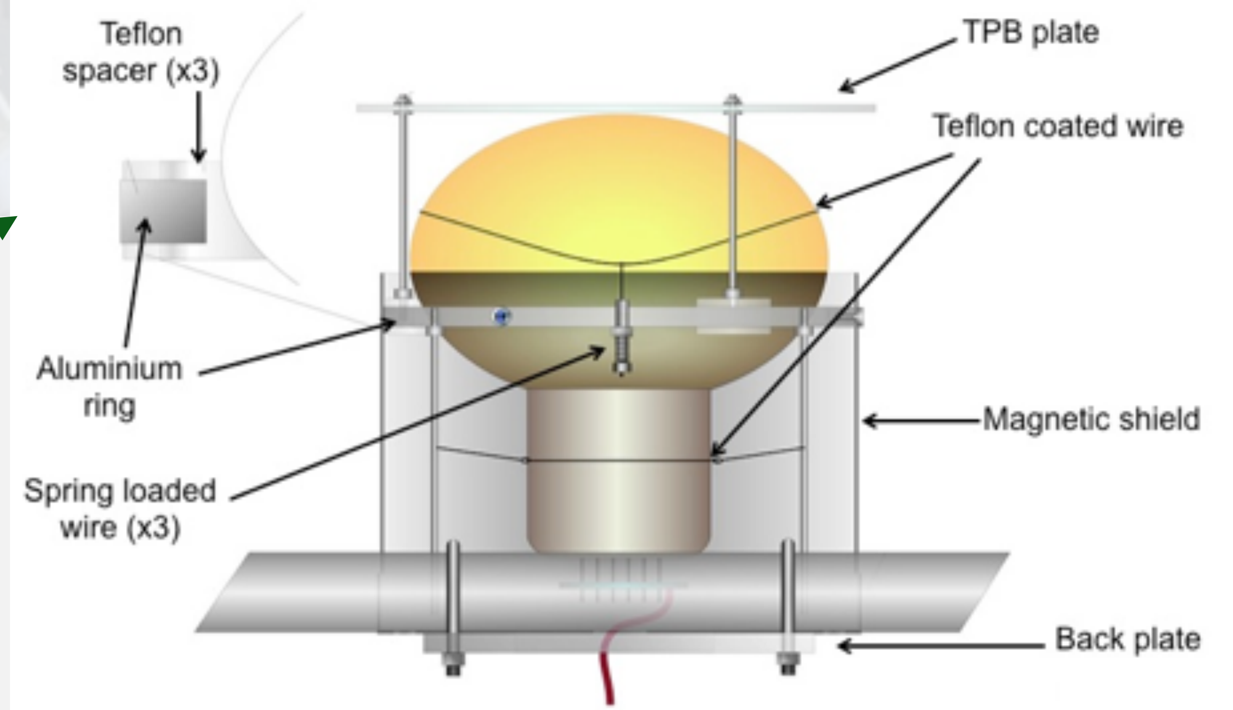


MicroBooNE Photon Detectors

32 PMTs + 4 light guide paddles

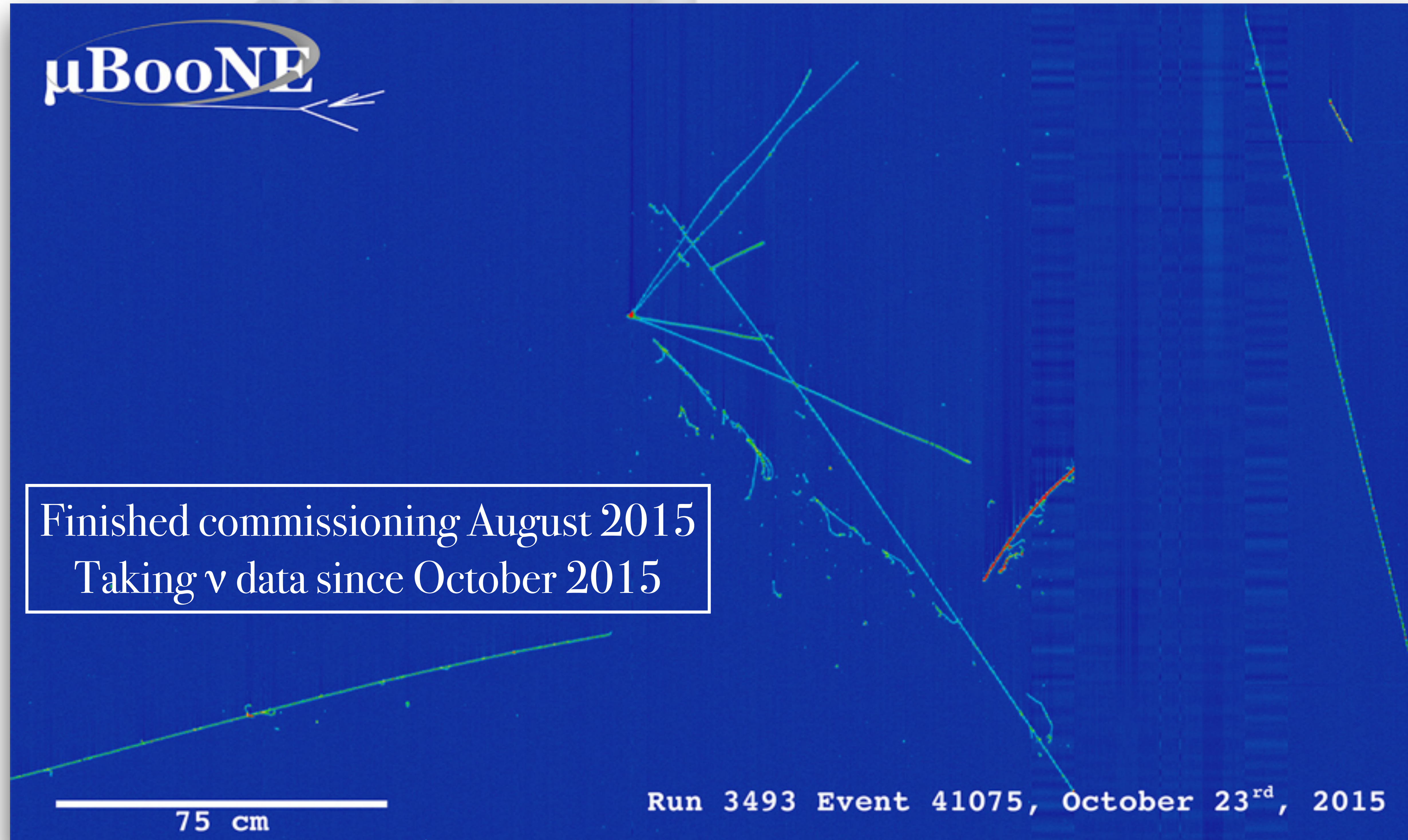


PMT mount with a PMT



A wire ring is pulled down by 3 spring loaded wires to an aluminium ring.
Direct contact of the PMT to the aluminium ring is avoided by Teflon blocks.
The magnetic shield and the TPB plate are fixed on to the PMT mount.

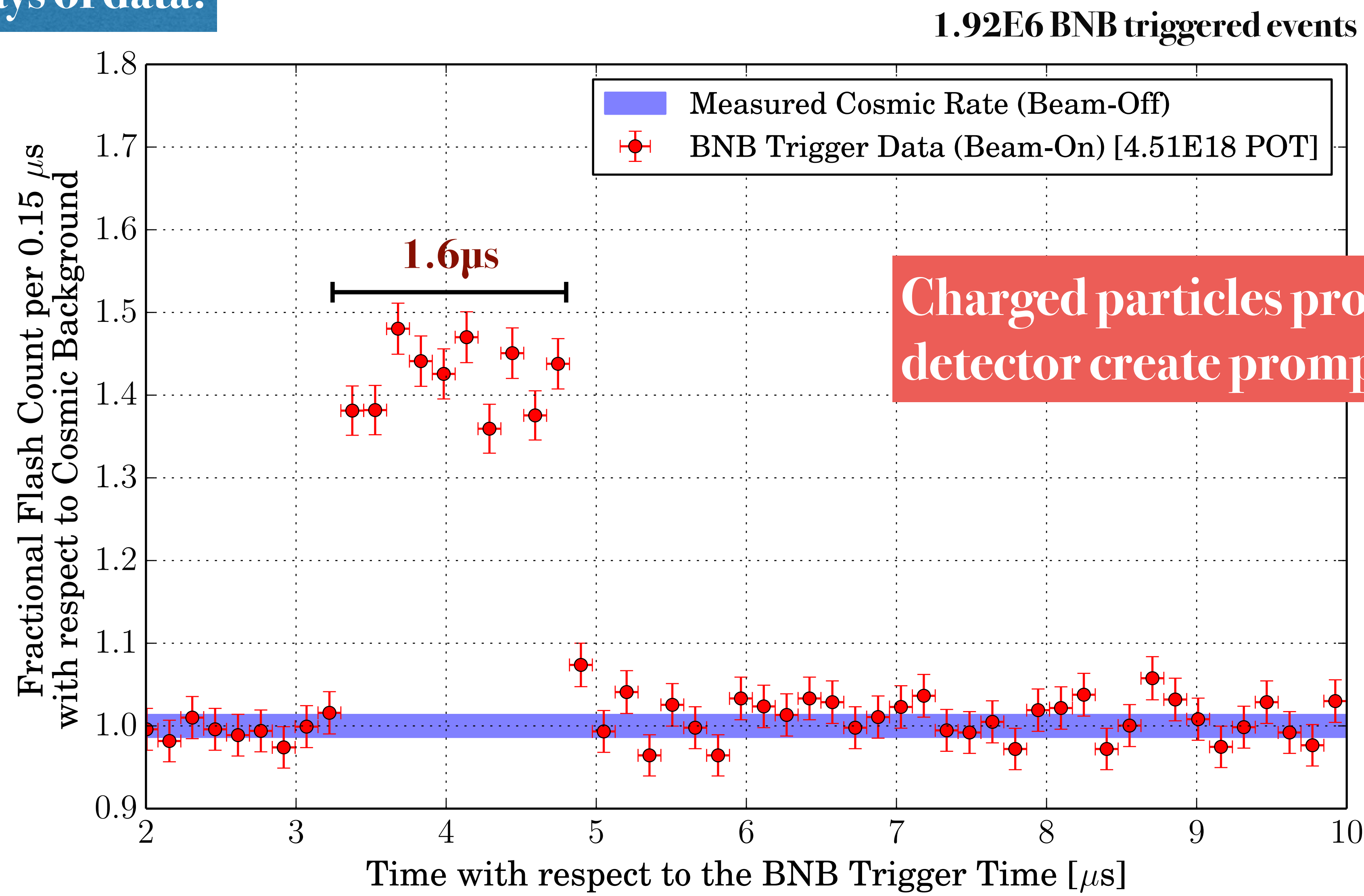
MicroBooNE Physics



Finished commissioning August 2015
Taking ν data since October 2015

MicroBooNE Physics

From the first days of data!

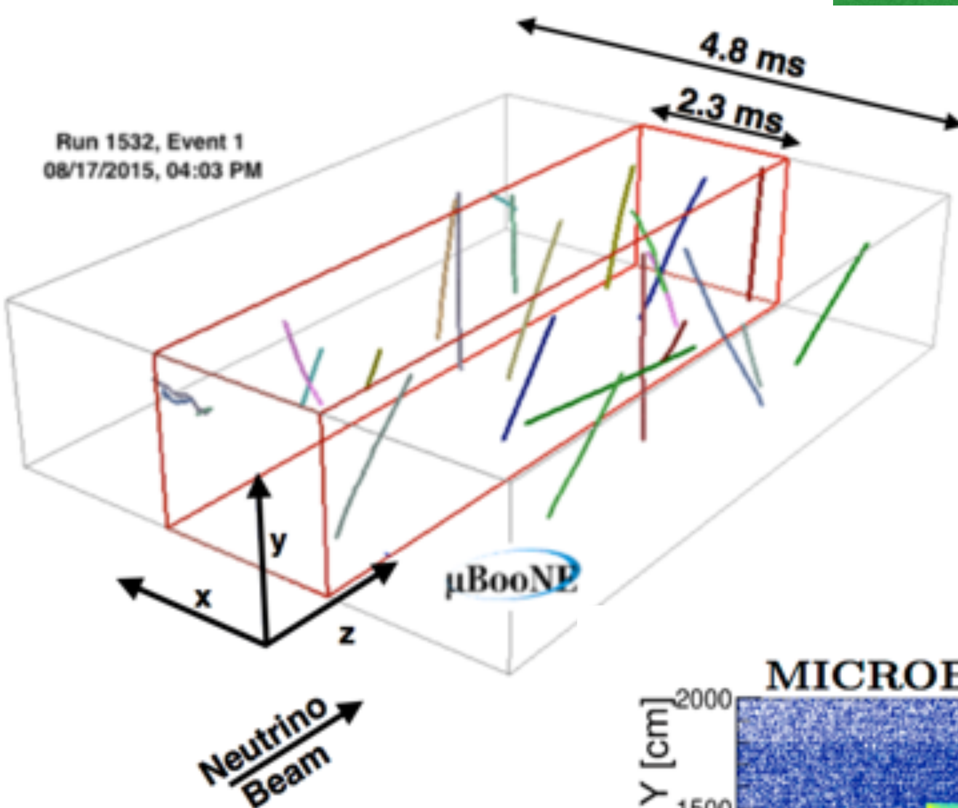


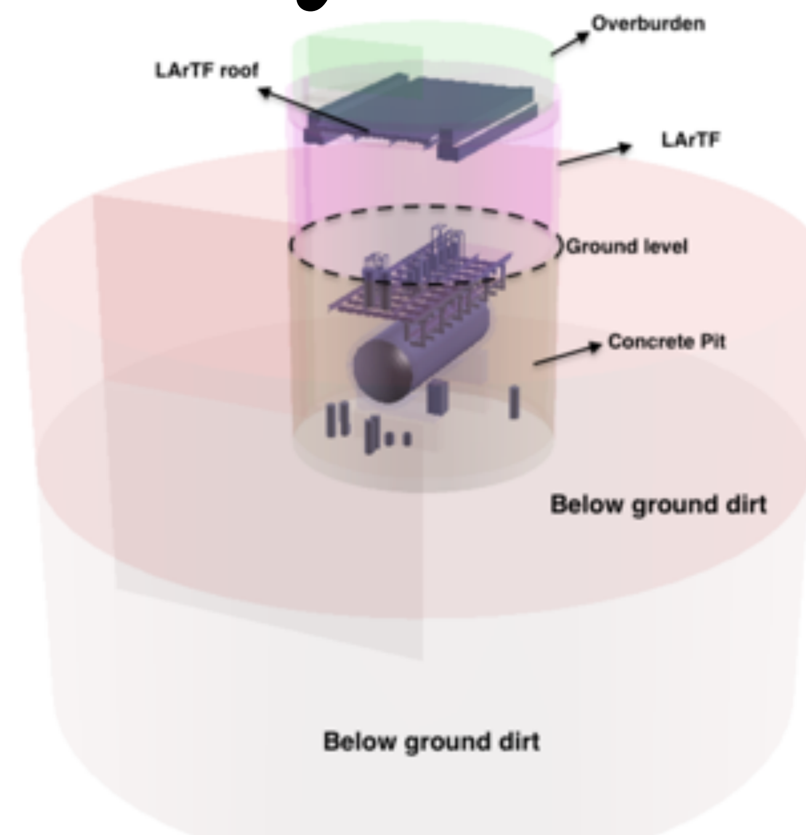
Charged particles produced inside the detector create prompt scintillation light.

A clear excess can be seen due to neutrinos between 3 and 5 μs after the trigger.

MicroBooNE Cosmic Physics

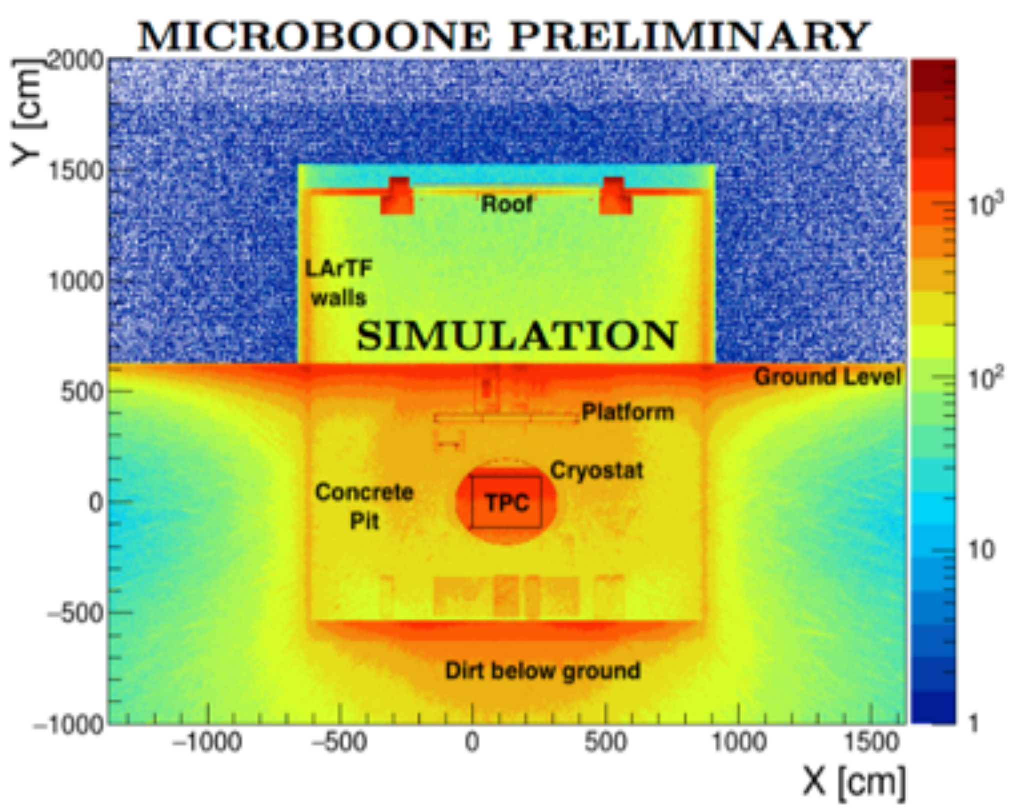
Cosmic data is used for the characterization of the detector.

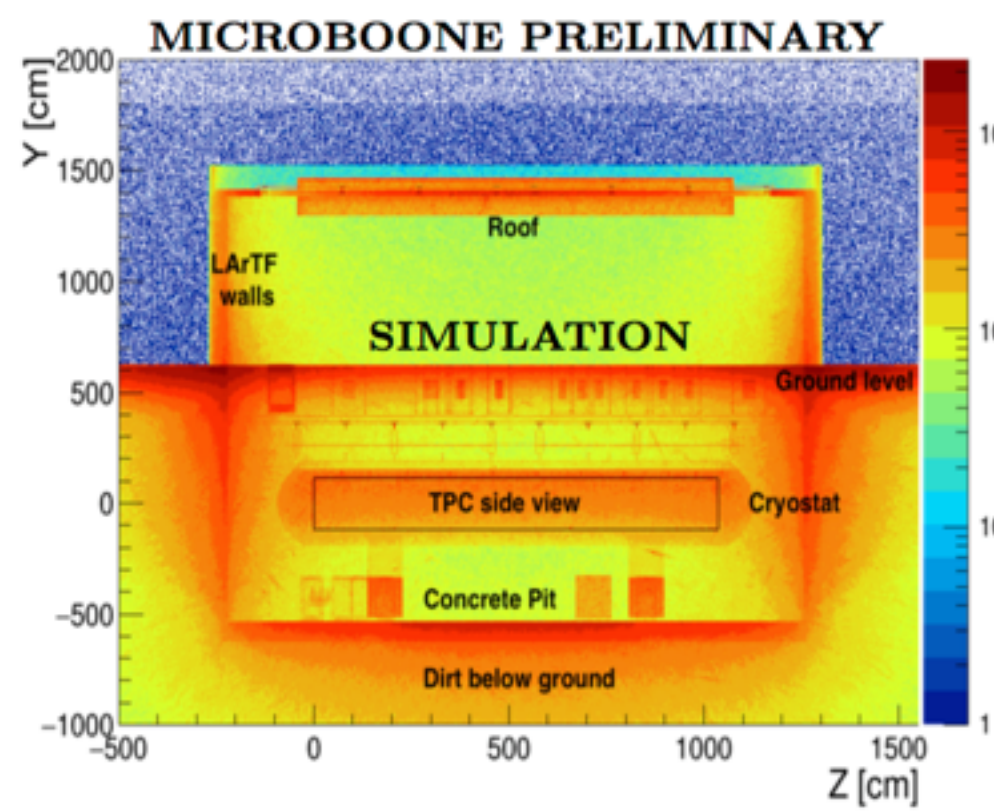




drift time of 2.3 ms

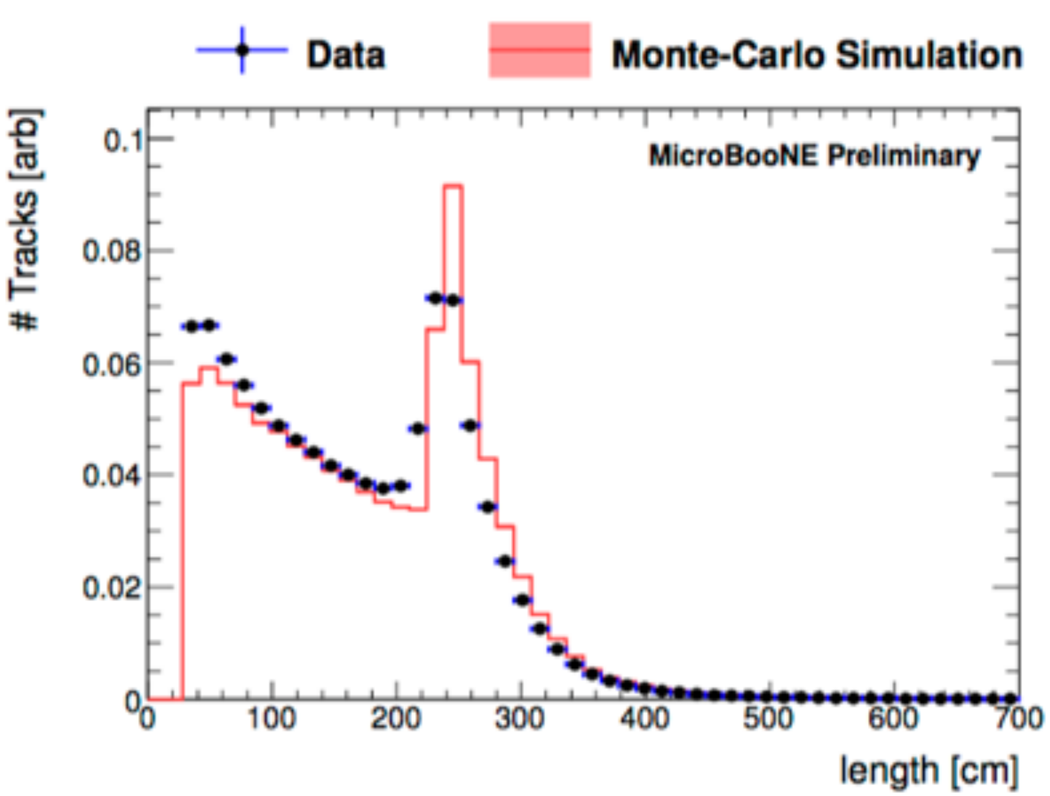
readout time 4.8 ms

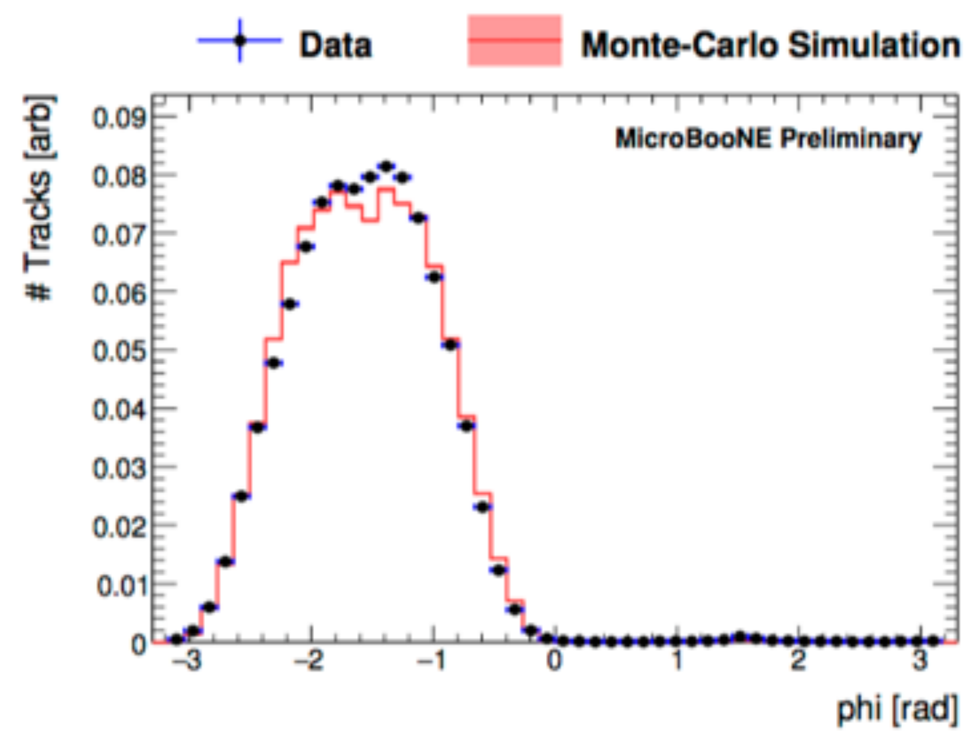




MicroBooNE Cosmic Physics

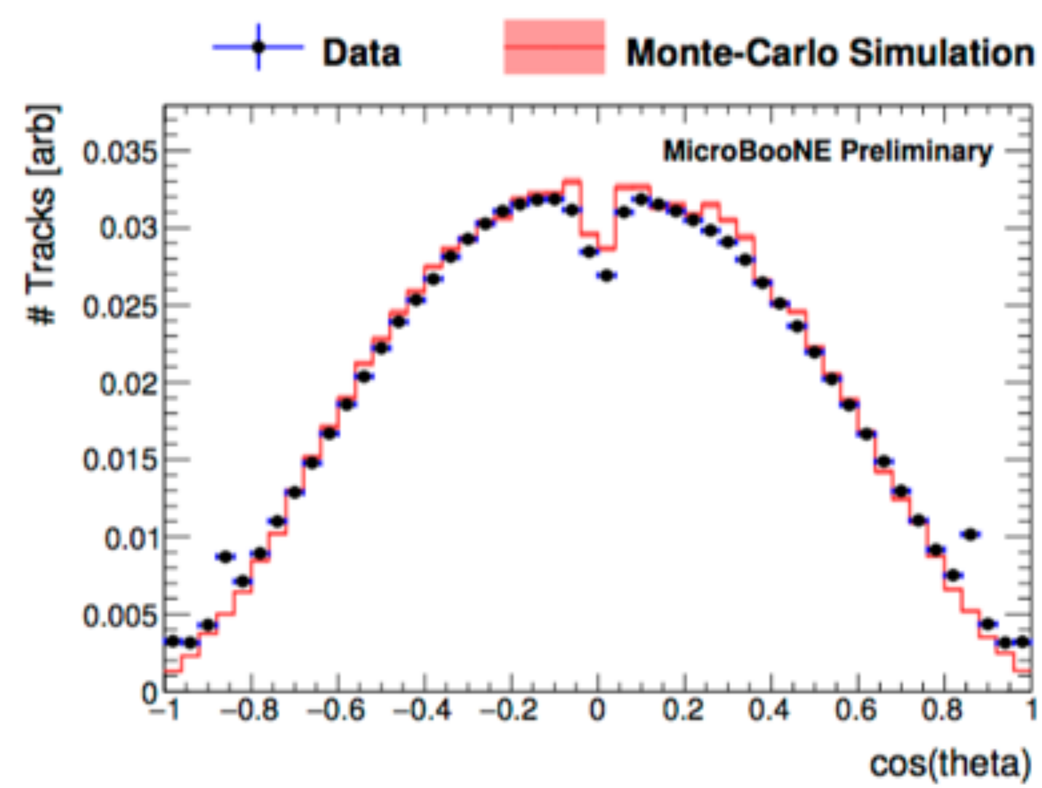
We combine hit information from the 3 planes to reconstruct 3D objects





Area normalized

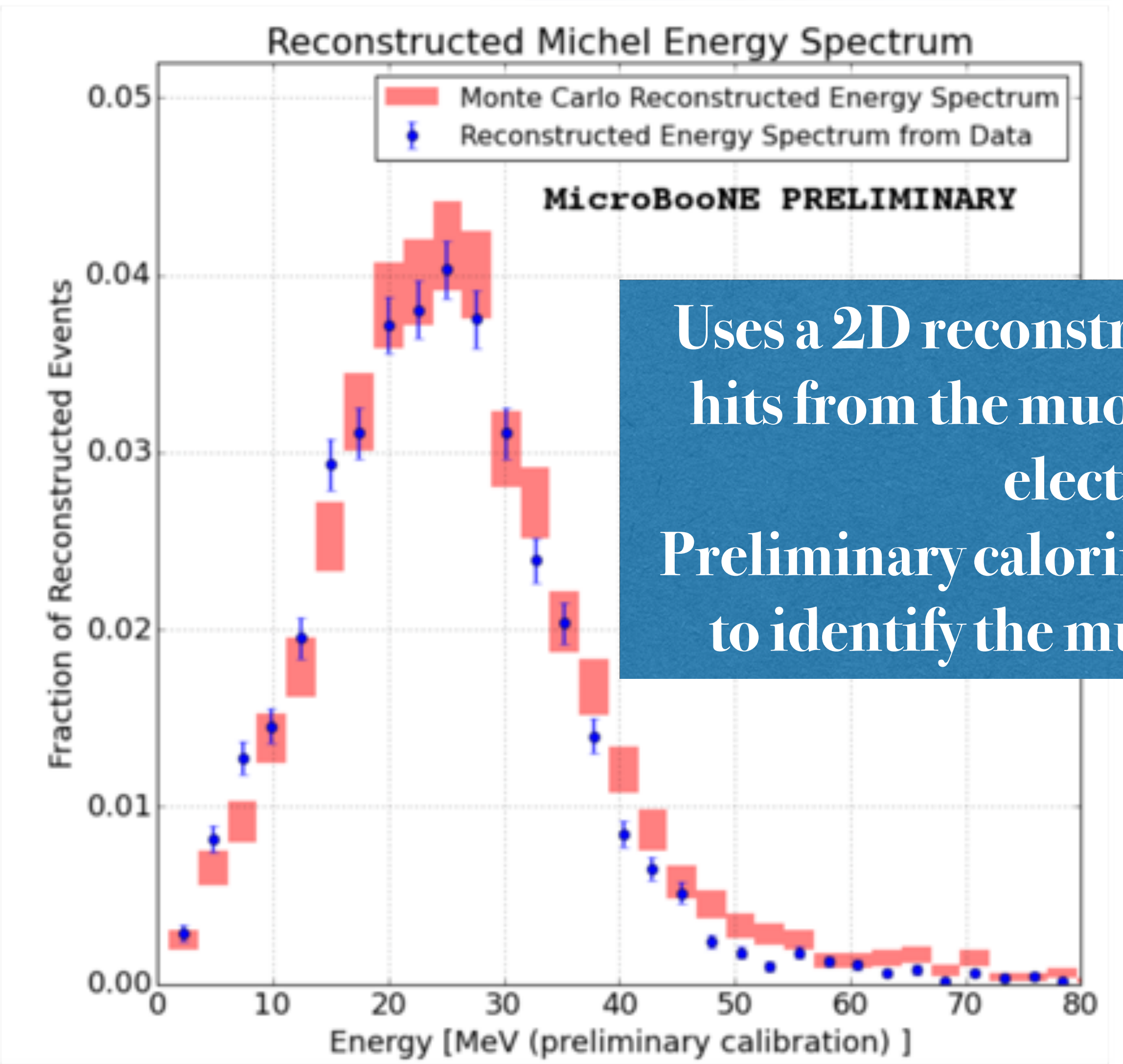
Data/MC comparison for Cosmic events



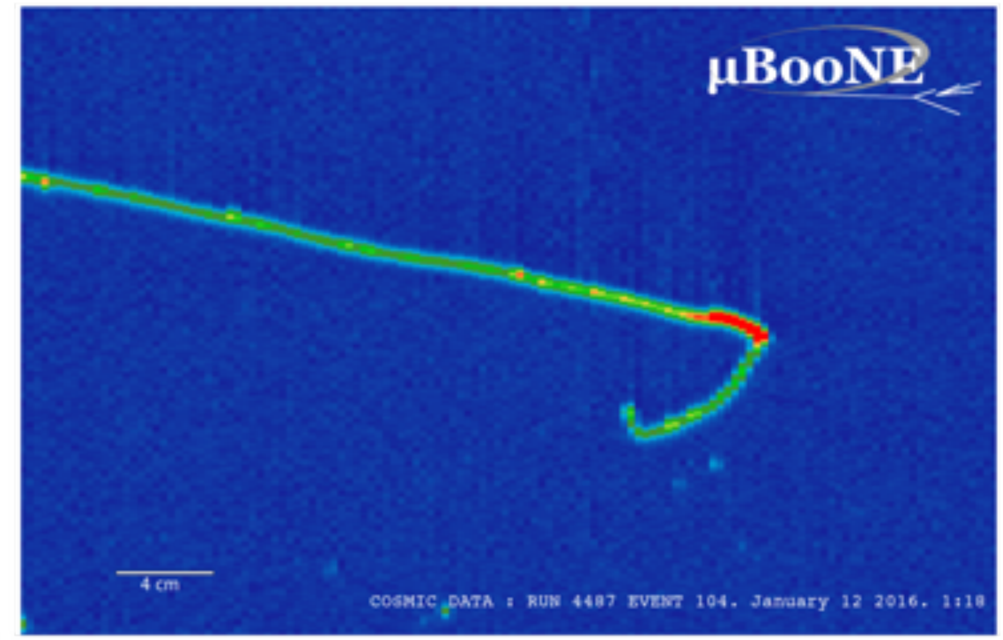
MICROBOONE-NOTE-1014-PUB

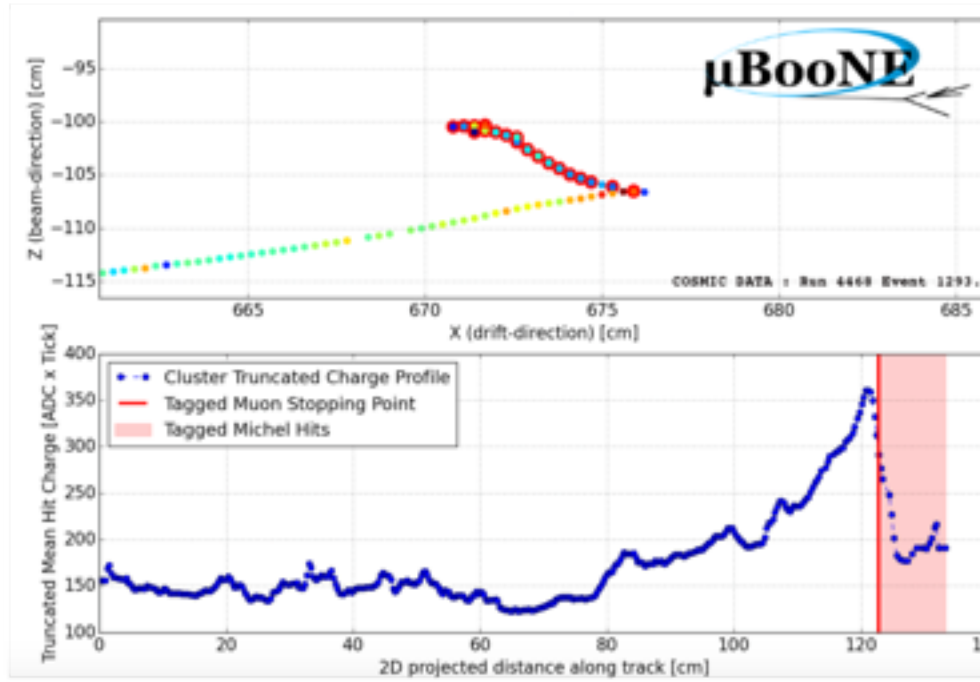
MicroBooNE Michel Electrons

Studies done using cosmic events



Uses a 2D reconstruction to identify hits from the muon and the Michel electron.
Preliminary calorimetric calibration to identify the muon Bragg peak.





$$E(\mathrm{MeV}) = Q(e^-) \times \frac{23.6}{10^6}\left[\frac{MeV}{e^-}\right] \times 1.16[\mathrm{Lifetime\ Corr.}] \times \frac{1}{0.62}[\mathrm{Recombination\ Corr.}]$$

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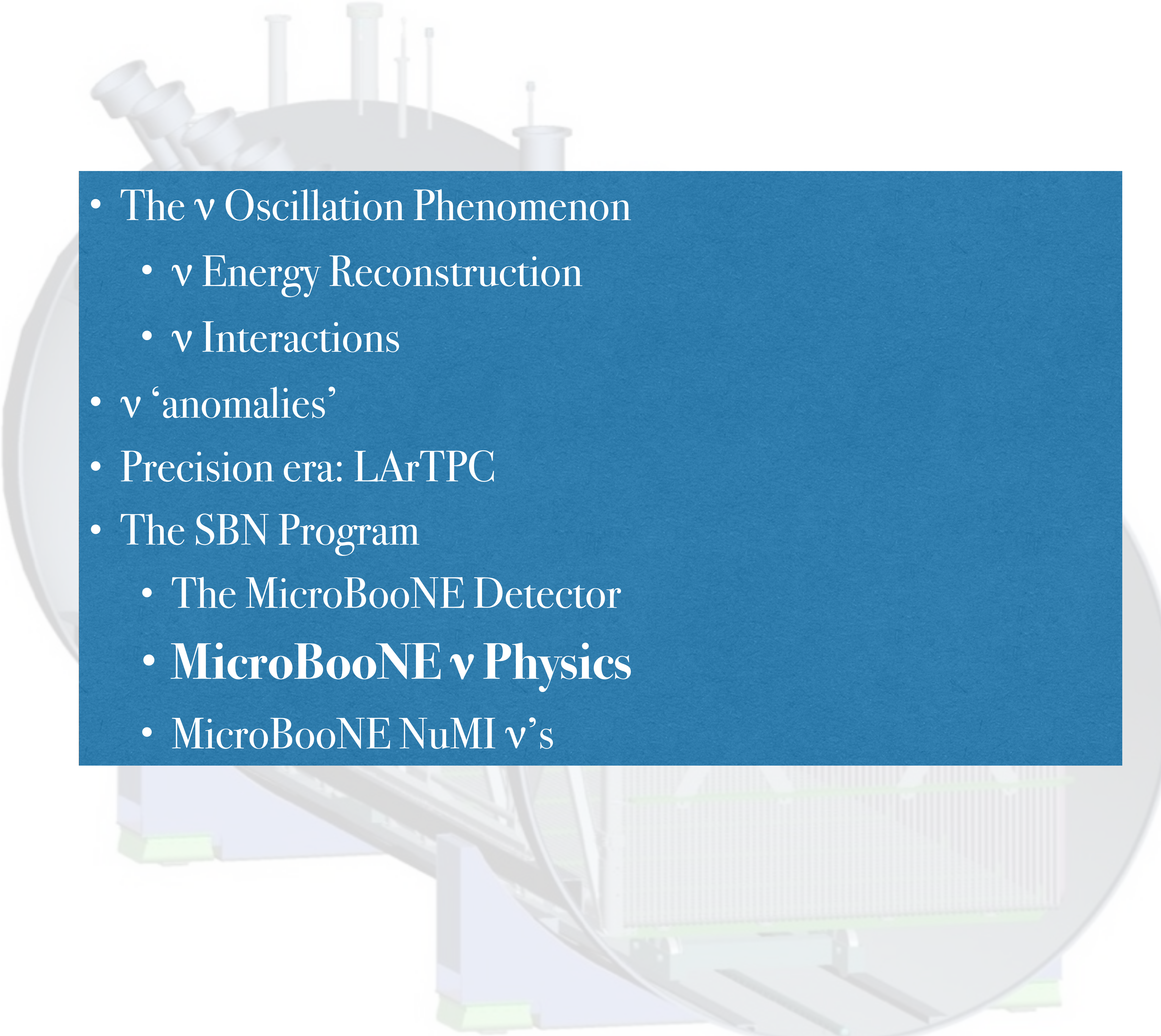
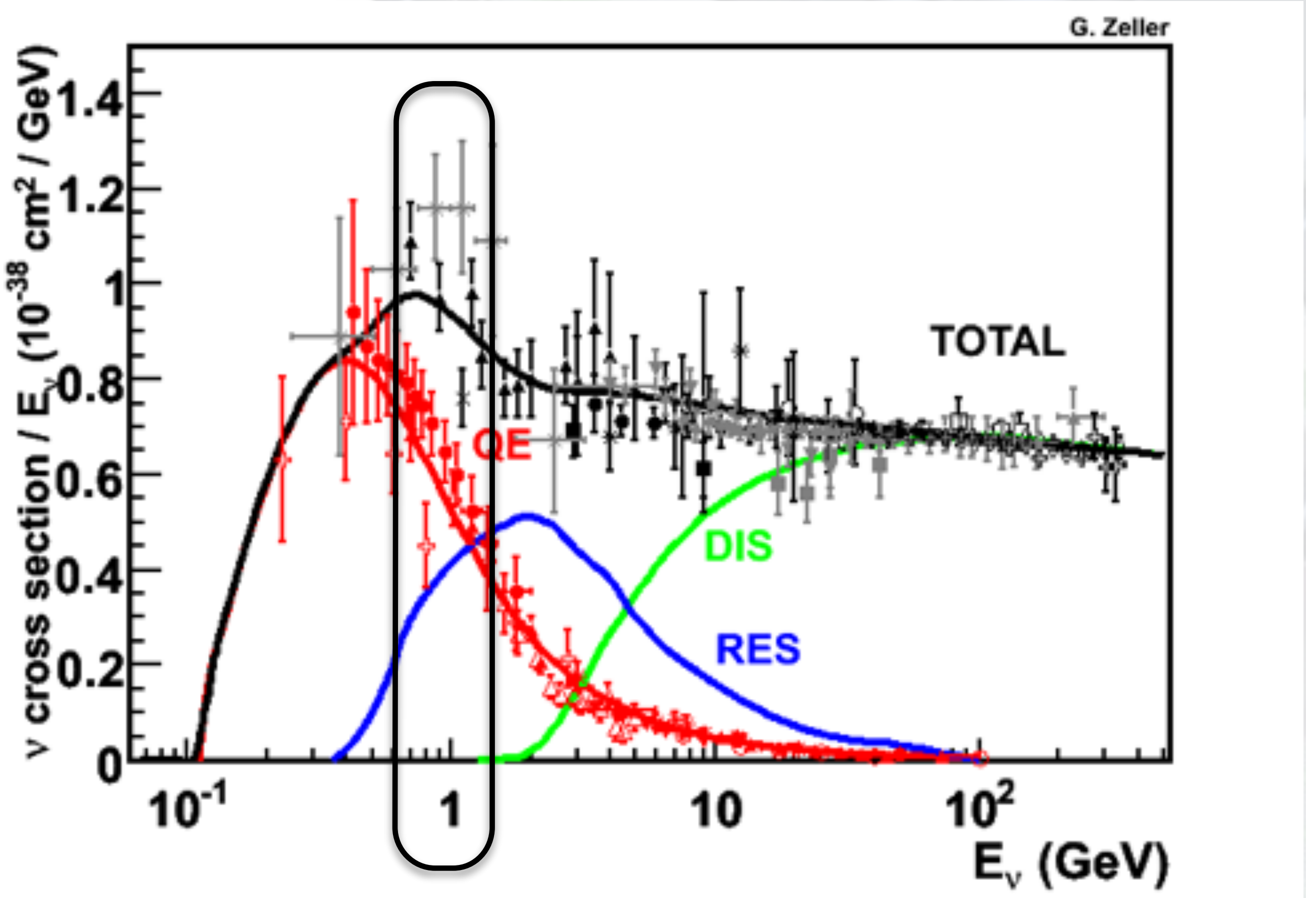
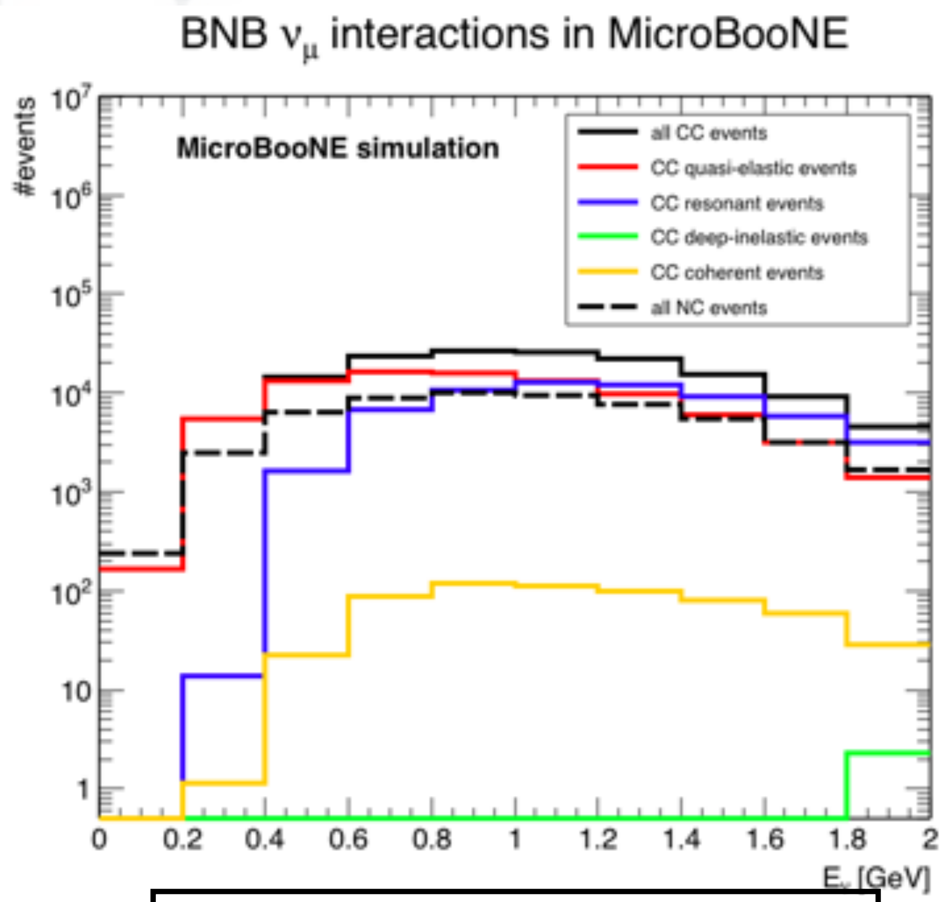


- The ν Oscillation Phenomenon
  - ν Energy Reconstruction
  - ν Interactions
- ν ‘anomalies’
- Precision era: LArTPC
- The SBN Program
  - The MicroBooNE Detector
  - **MicroBooNE ν Physics**
  - MicroBooNE NuMI ν’s

MicroBooNE ν Physics

We need to understand all the possible differences from our data to the current simulations



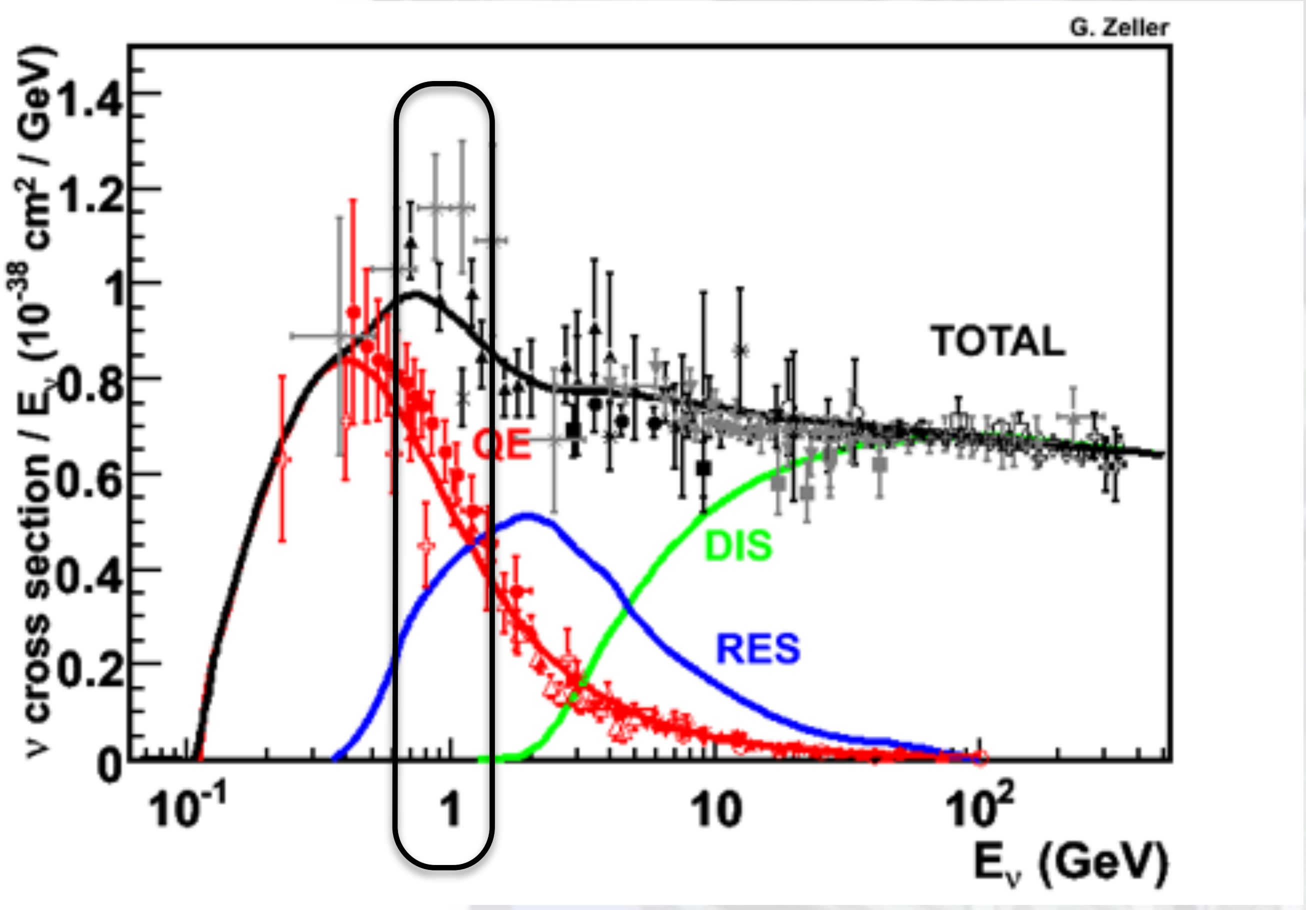


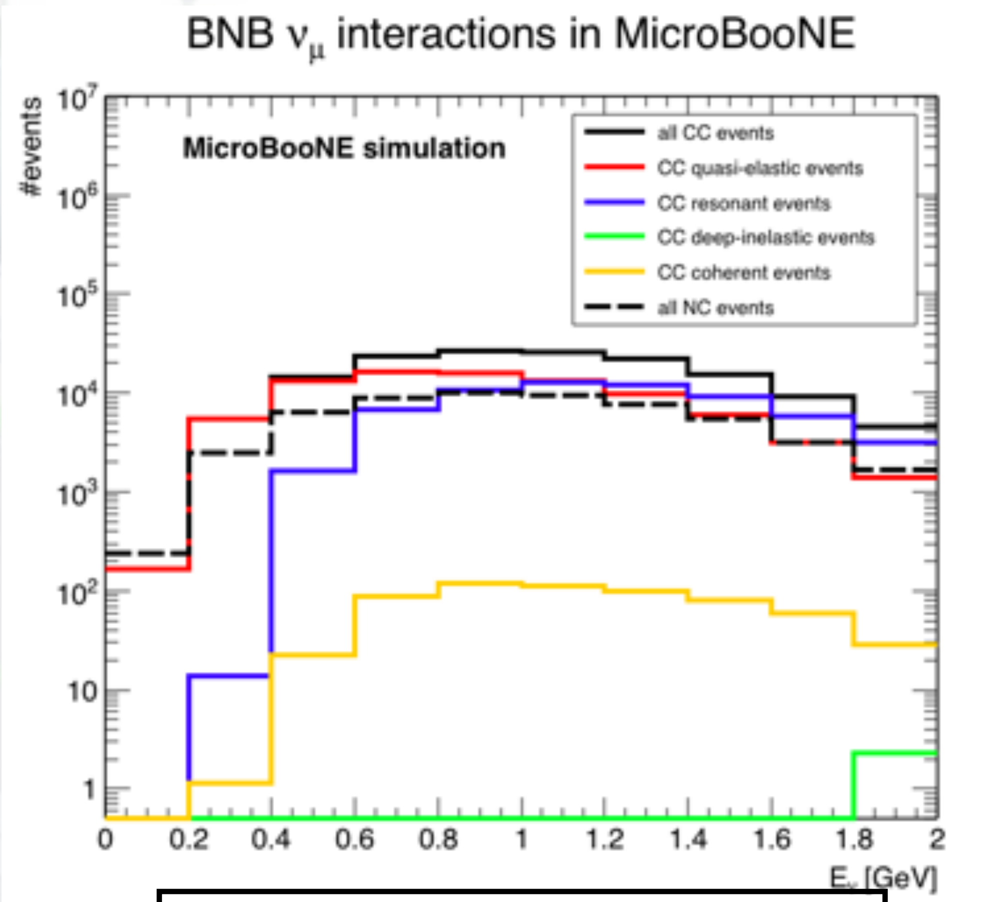
Using GENIE without MEC

Present and future ν oscillation experiments cover a region full of reaction thresholds and sparse data.

MicroBooNE ν Physics

We need to understand all the possible differences from our data to the current simulations





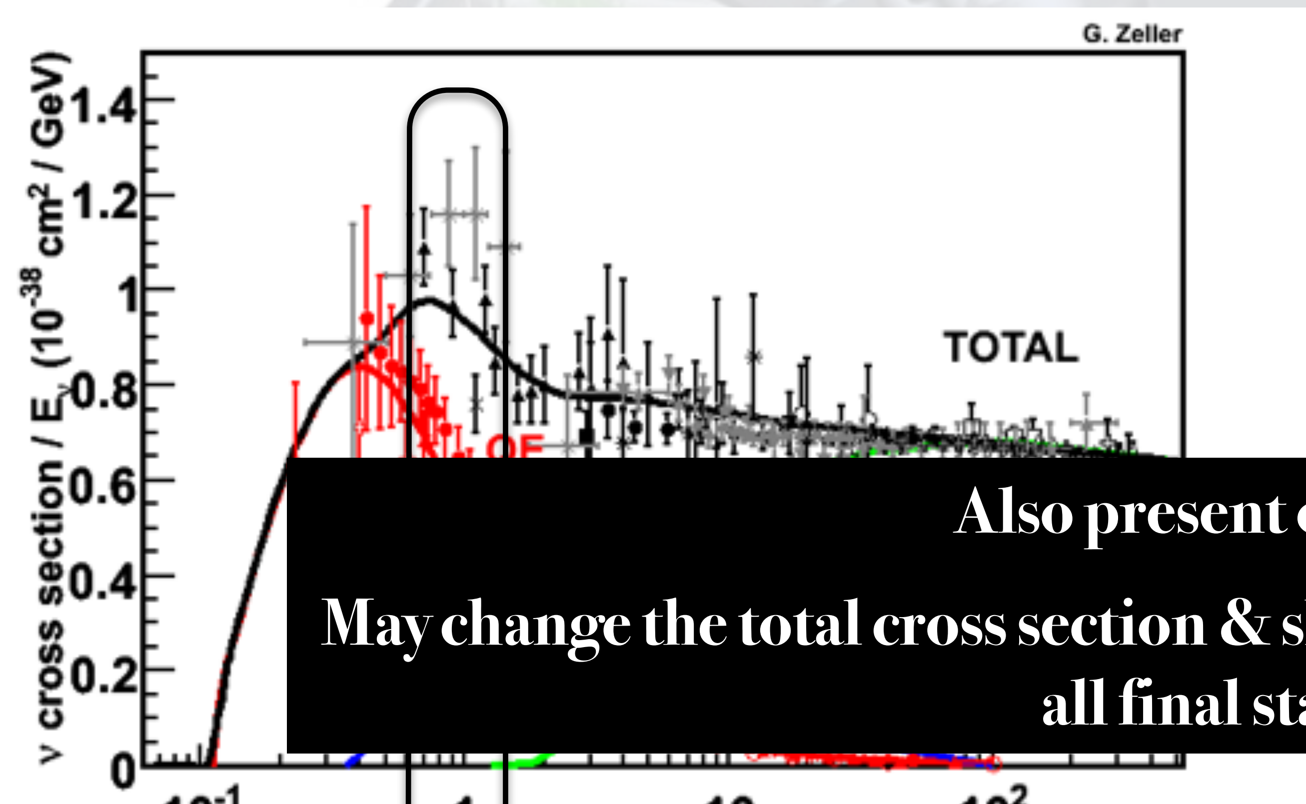
Using GENIE without MEC

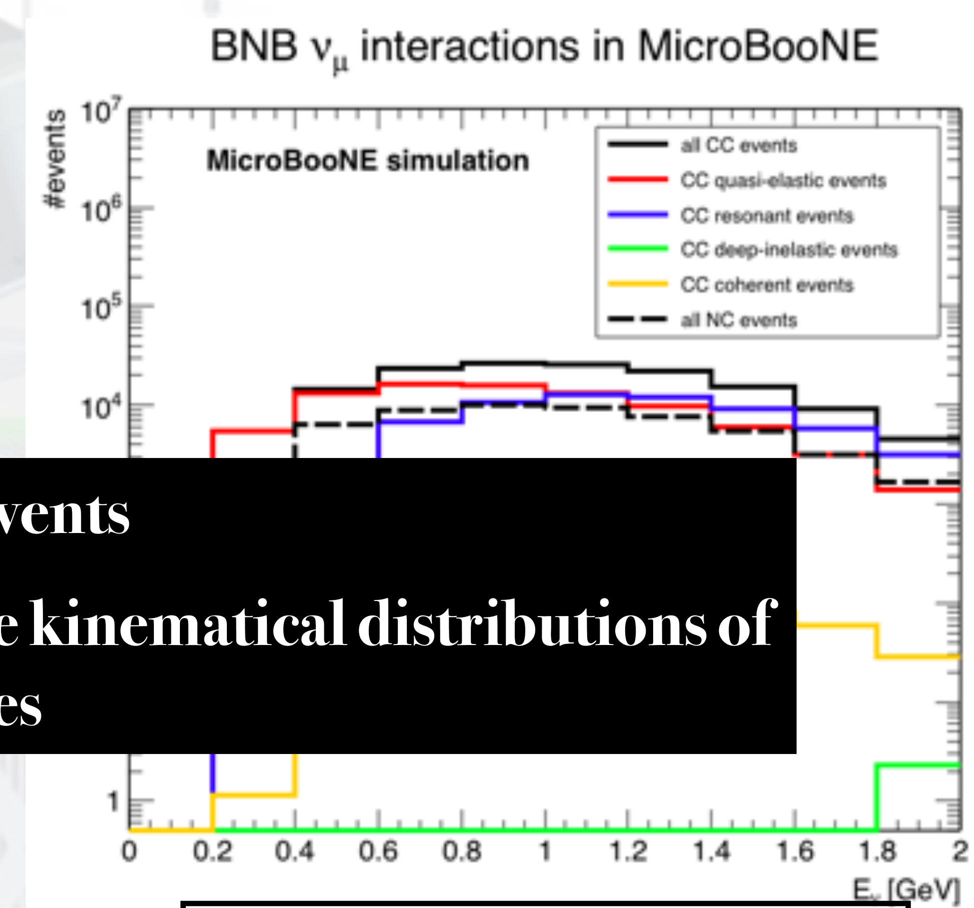
Current predictions (GENIE & NuWRO) advance a huge contribution of MEC interactions (20% in ν_μ CC).

Even if resonant π production and MEC interactions are big contributions, due to FSI we expect to see mostly $CC0\pi^{+/-/0}$ events.

MicroBooNE ν Physics

We need to understand all the possible differences from our data to the current simulations





Also present on the ν_e events

May change the total cross section & shape of the kinematical distributions of all final state particles

Particularly important at low Q^2 interactions

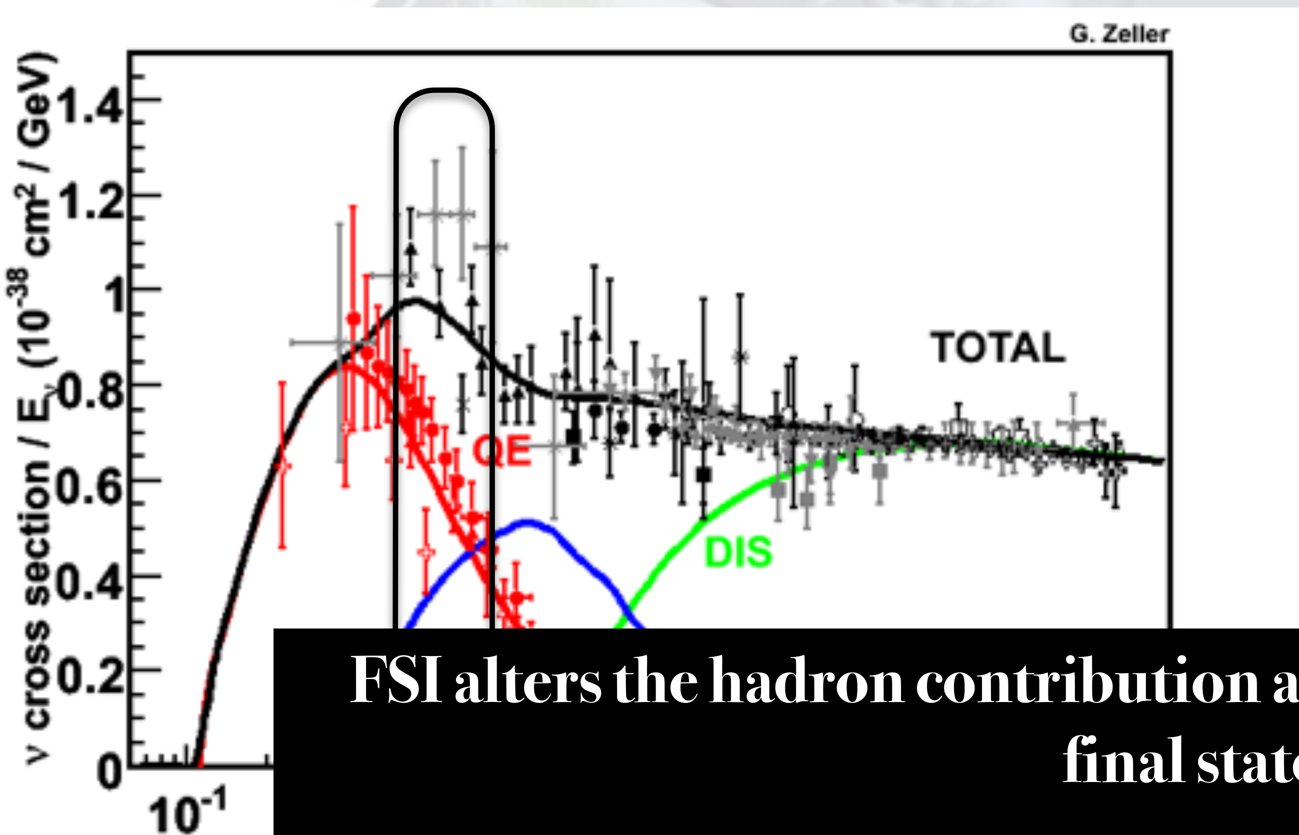
Using GENIE without MEC

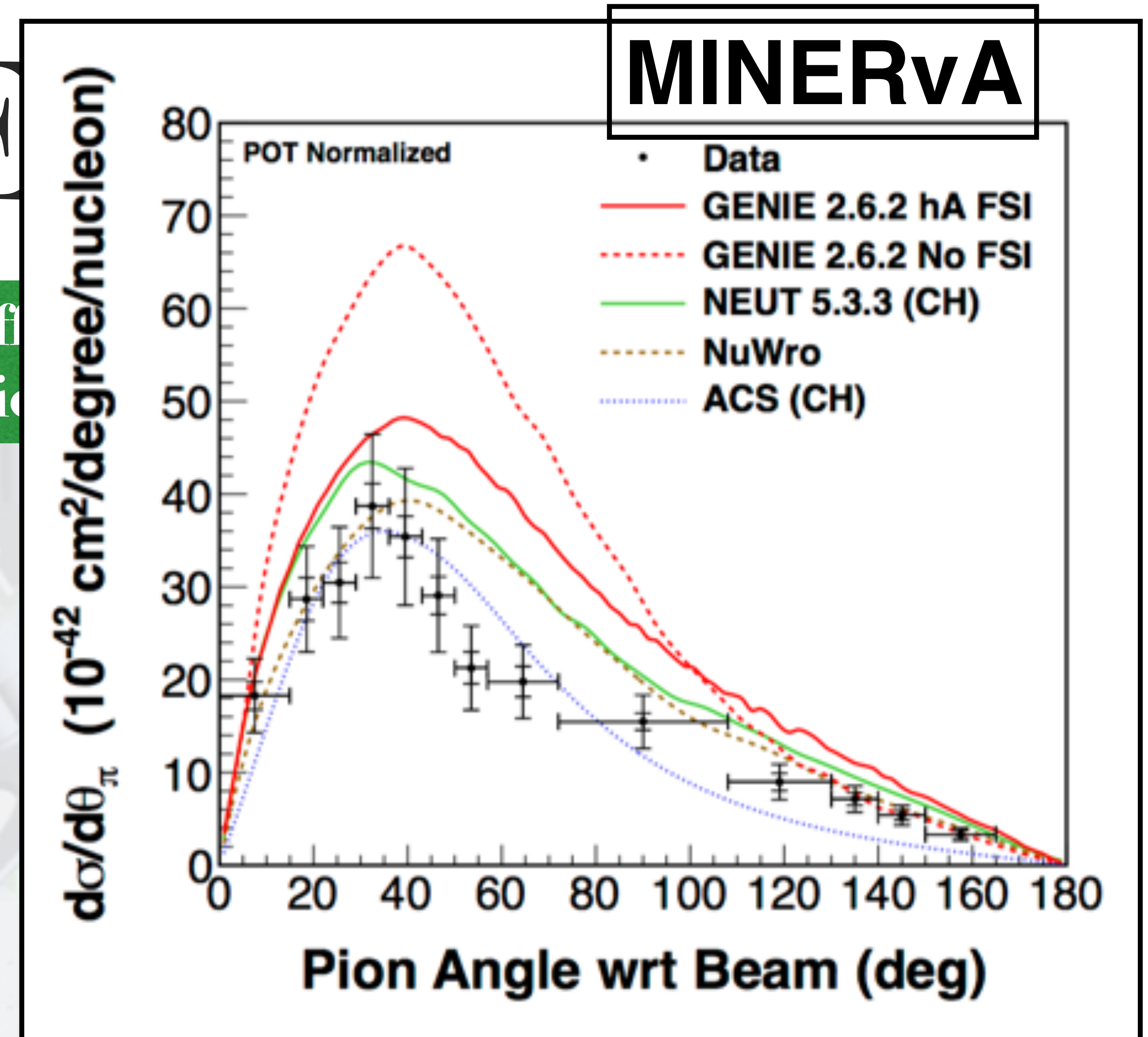
Current predictions (GENIE & NuWRO) advance a huge contribution of MEC interactions (20% in ν_μ CC).

Even if resonant π production and MEC interactions are big contributions, due to FSI we expect to see mostly CC0$\pi^{+/-/0}$ events.

MicroBooNE

We need to understand all the possible dif
simulati





FSI alters the hadron contribution and the shape of the kinematics for the final state hadrons:

reconstructed visible energy is altered

Using GENIE without MEC

Increases difficulty on separate resonant vs MEC

RO) ad a huge contribution of MEC interactions (20% in ν_μ CC).

Even if resonant pion production and MEC interactions are big contributions, due to FSI we expect to see mostly CC0$\pi^{+/-/0}$ events.

MicroBooNE ν Physics

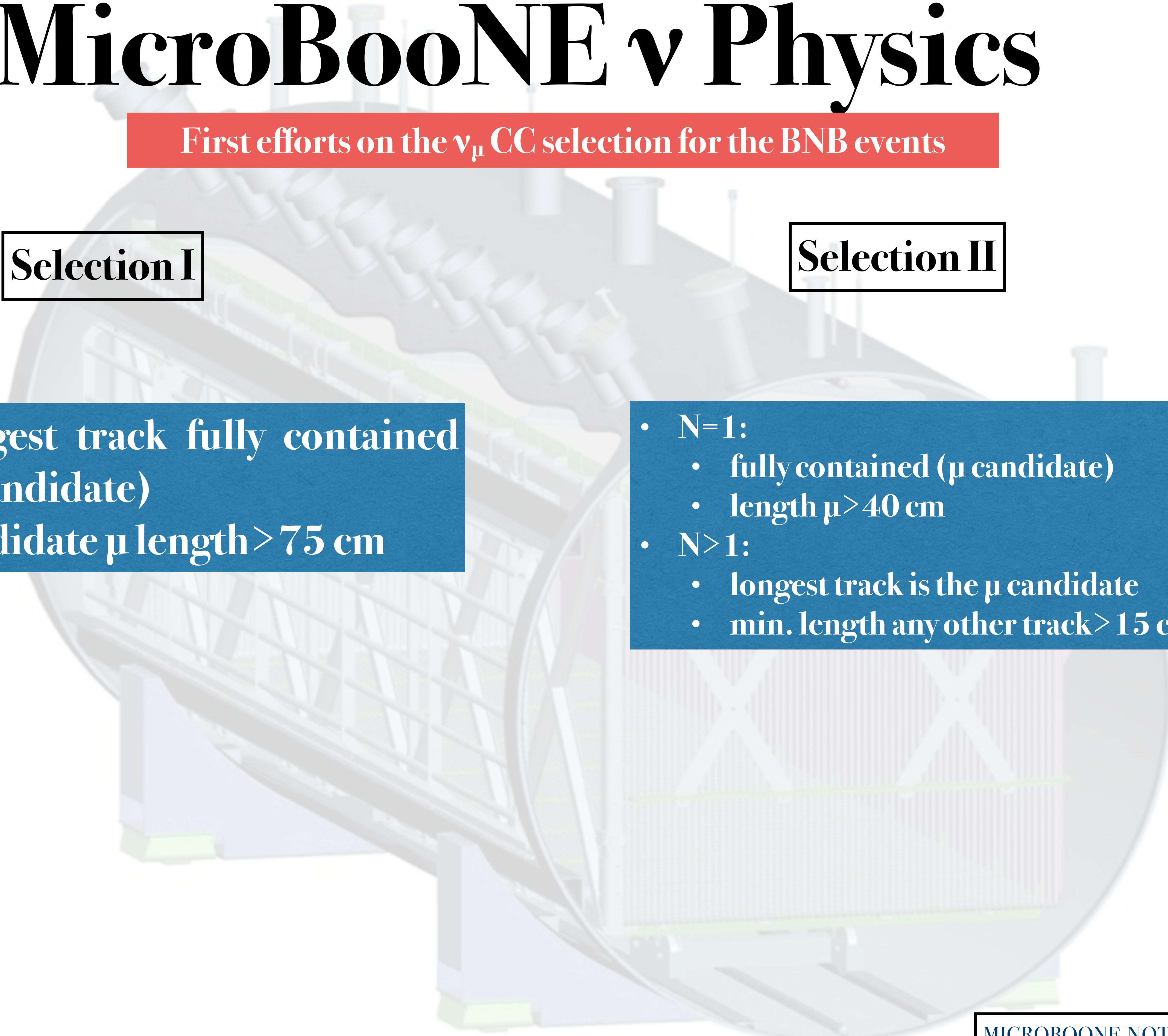
First efforts on the ν_μ CC selection for the BNB events

Inclusive ν_μ CC measurements motivation:

- Small theoretical bias (for the lepton kinematics).
- More robust channel for theorists to understand our data.
- No additional difficulties to compare along experiments.
  - This is a topology on what we all of us agree.
- Safer way, using double differential (p_μ,θ_μ), to distinguish different neutrino reaction regions (CCQE and resonant).

MicroBooNE ν Physics

First efforts on the ν_μ CC selection for the BNB events



Selection I

- Longest track fully contained (μ candidate)
- Candidate μ length > 75 cm

Selection II

- N=1:
  - fully contained (μ candidate)
  - length μ > 40 cm
- N>1:
  - longest track is the μ candidate
  - min. length any other track > 15 cm

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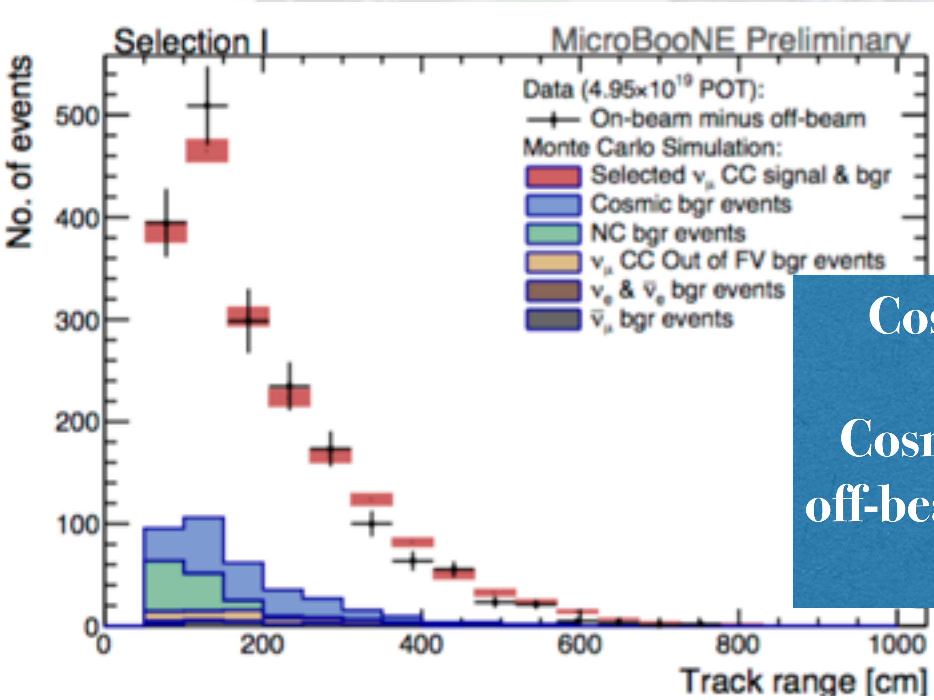
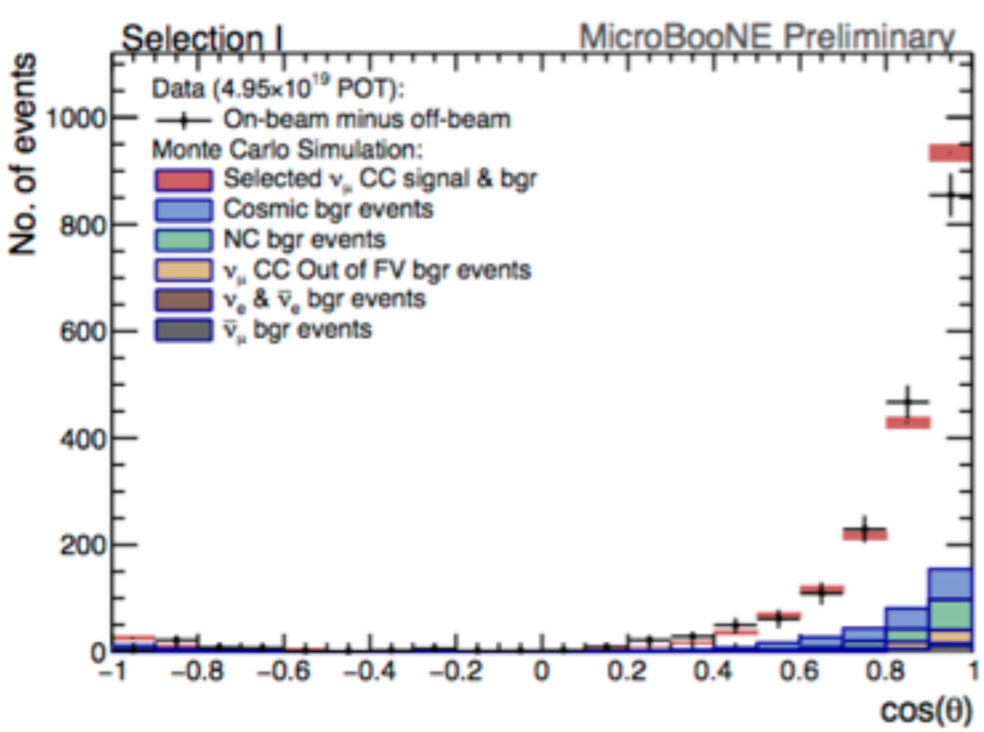
MicroBooNE ν Physics

First presented at NEUTRINO2016

First efforts on the ν_μ CC selection for the BNB events

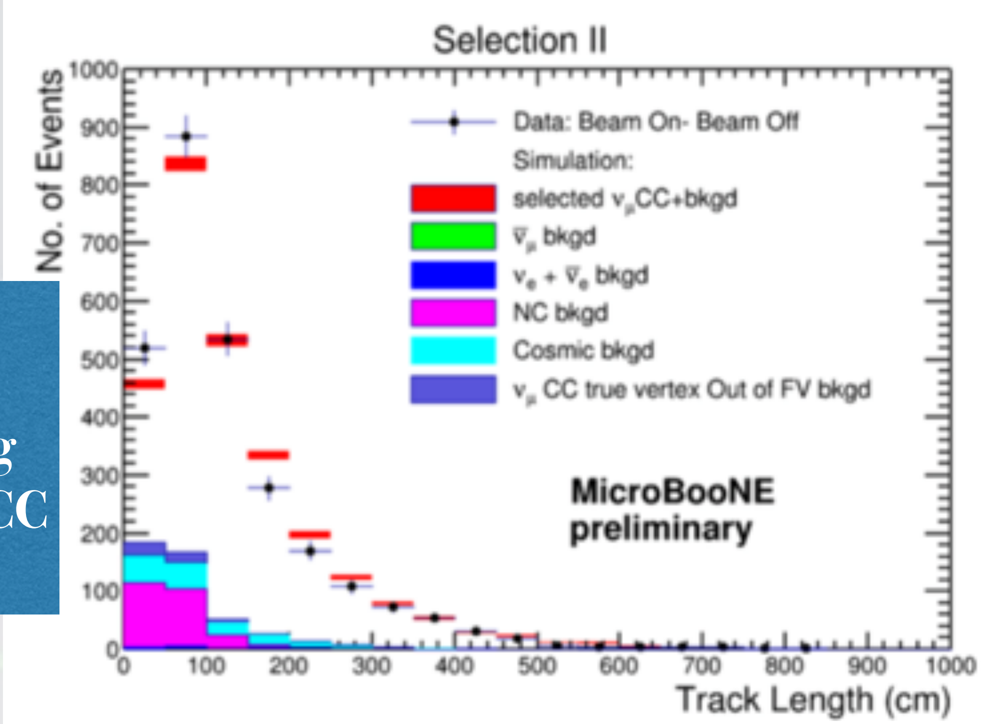
Selection I

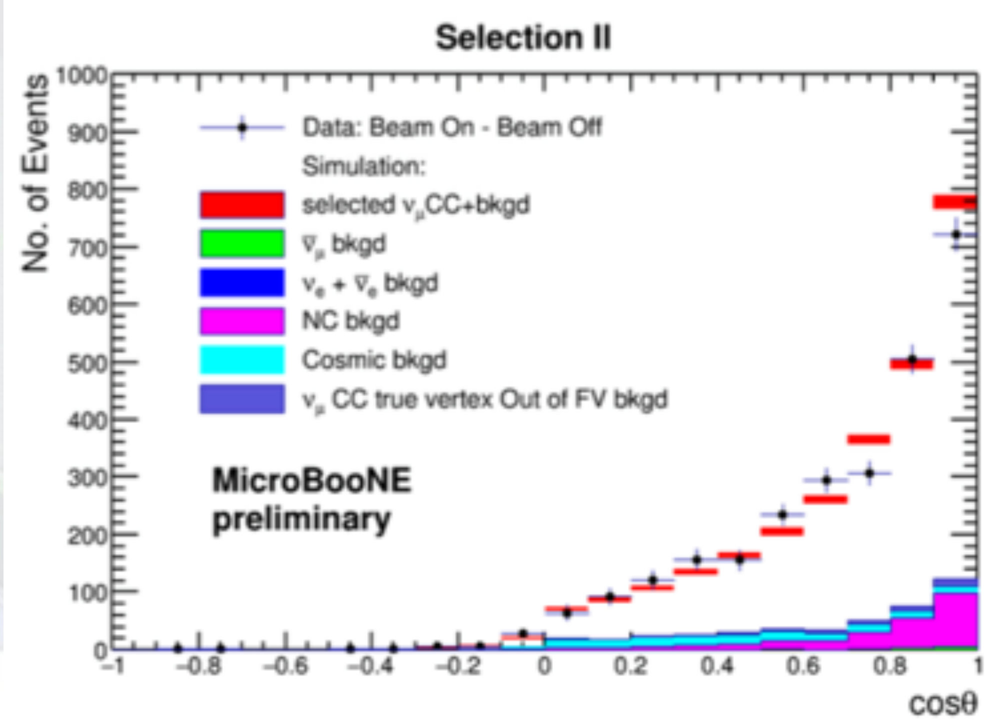




Cosmic contamination ~50%
Cosmic subtraction using off-beam data (passing ν_μ CC selection)

Selection II



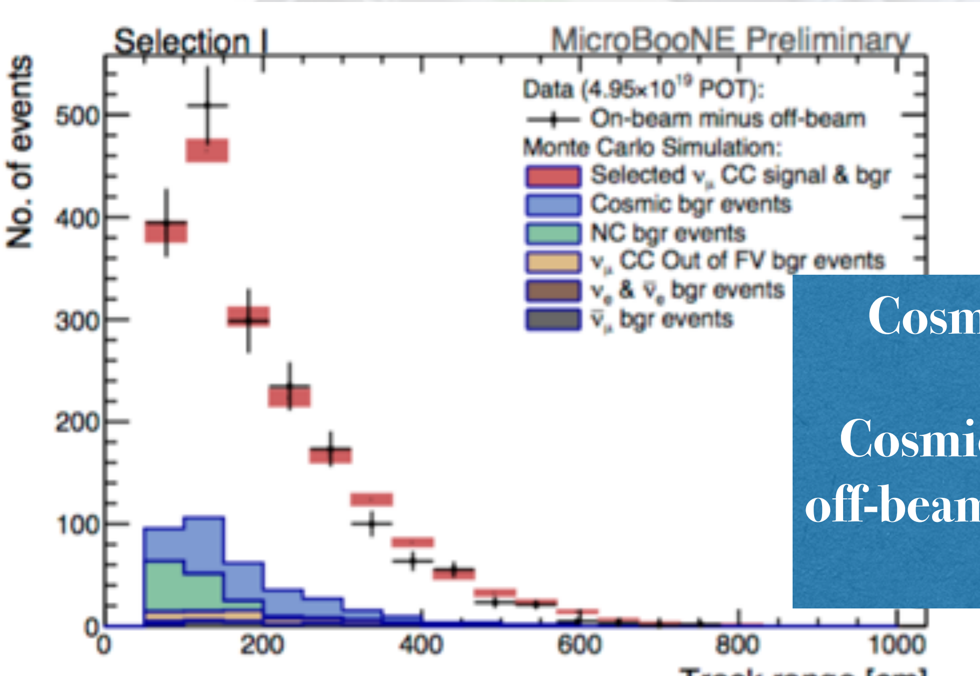


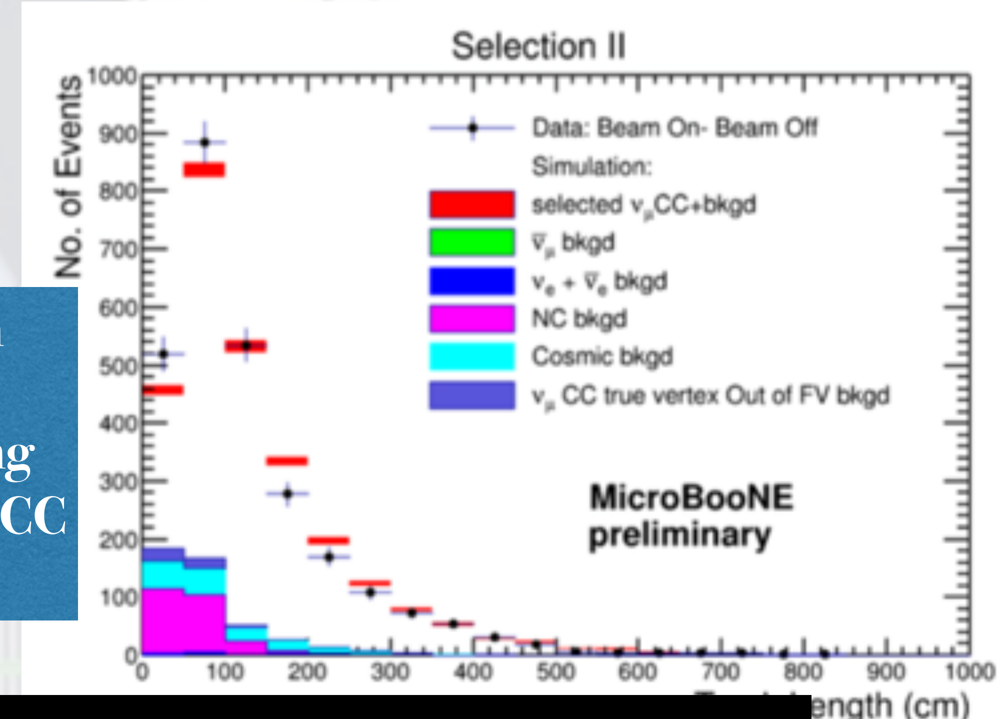
MicroBooNE ν Physics

First presented at NEUTRINO2016

First efforts on the ν_μ CC selection for the BNB events

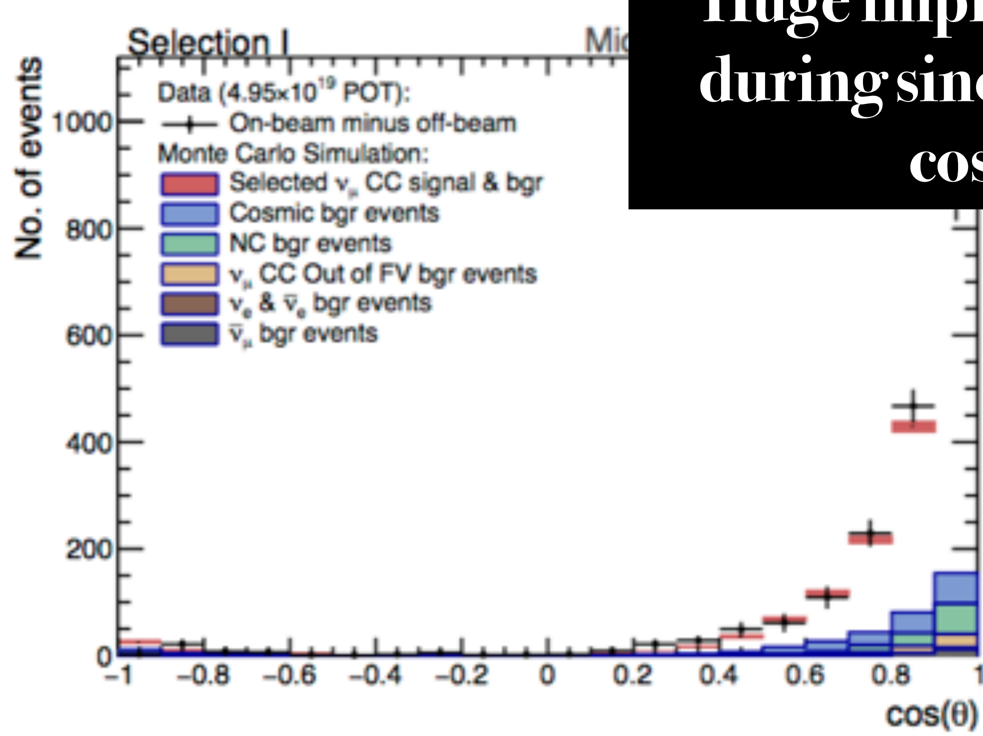
Selection I | **Selection II**

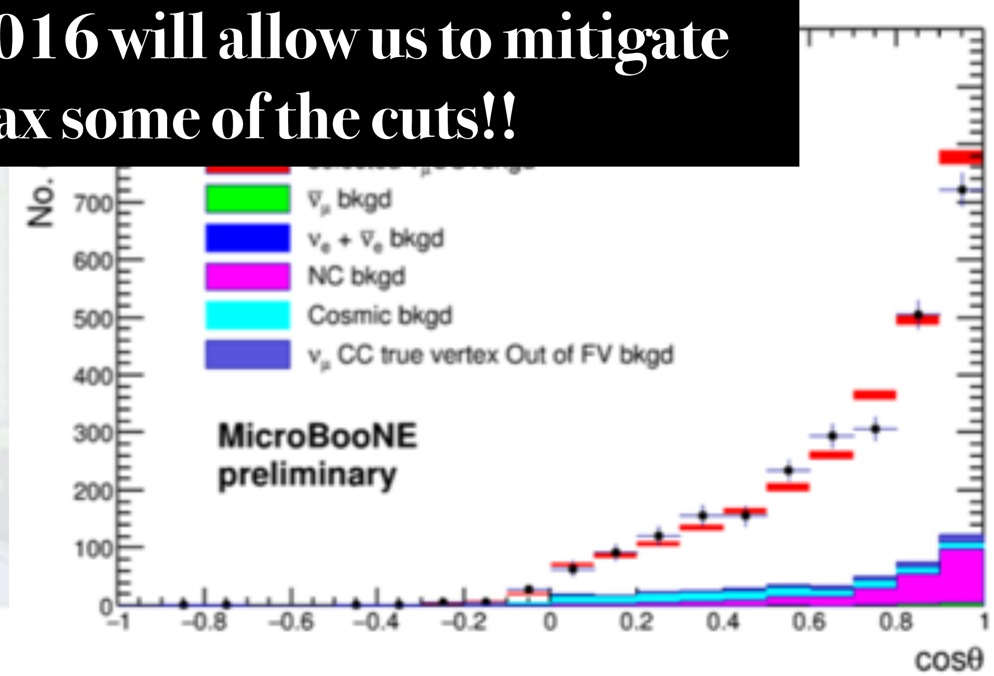




Cosmic contamination ~50%
Cosmic subtraction using off-beam data (passing ν_μ CC selection)

Huge improvements in reconstruction and simulation during since NEUTRINO2016 will allow us to mitigate cosmic bkg and relax some of the cuts!!

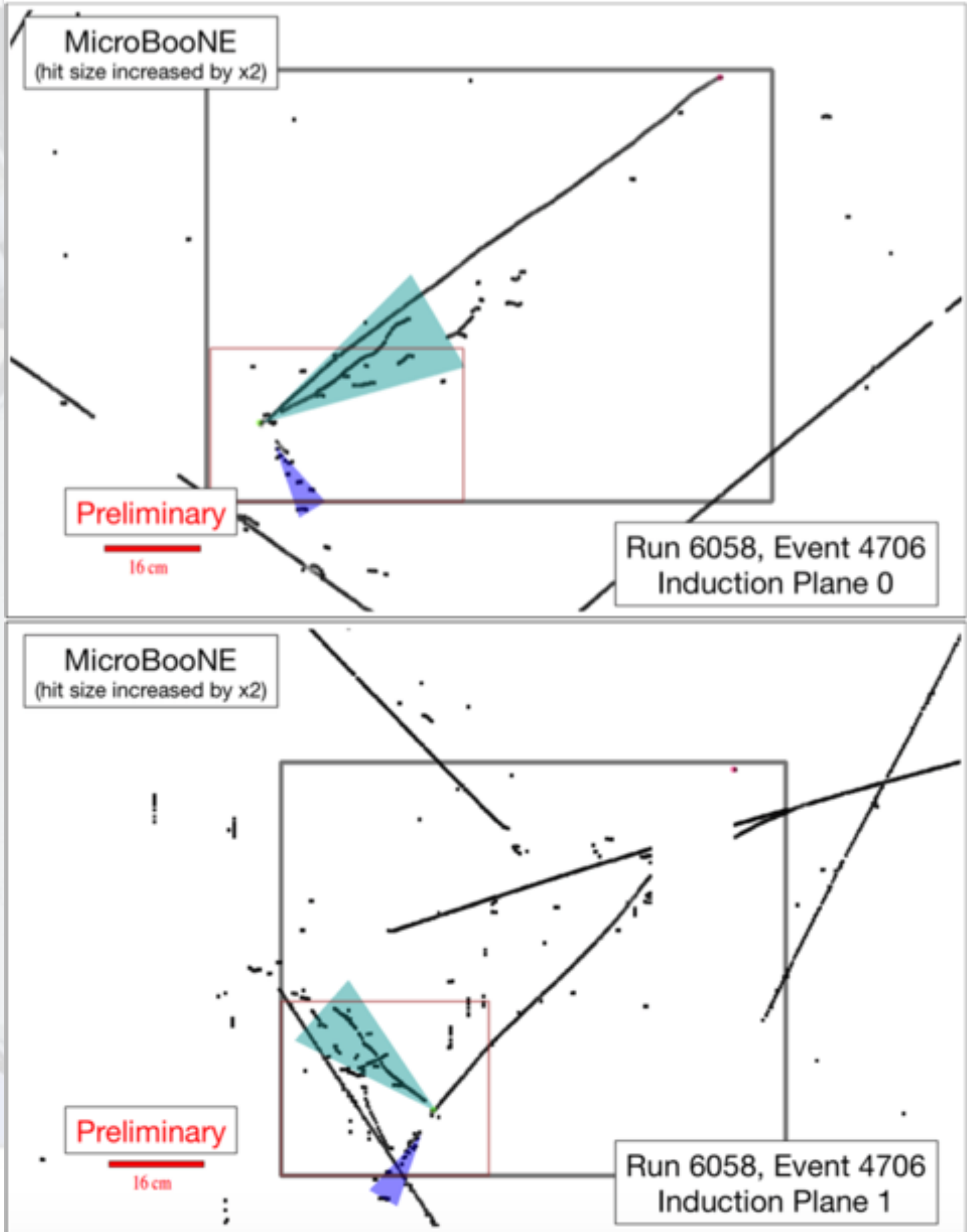




MicroBooNE ν Physics

First efforts on the ν_μ $CC\pi^0$ studies

- $CC\pi^0$ are one of the main bkg for ν_e.
- These cross section measurements showed poor prediction by the different MC wrt all available experimental data.
- Allow us to train our reconstruction algorithms to improve our shower efficiency and energy resolution.



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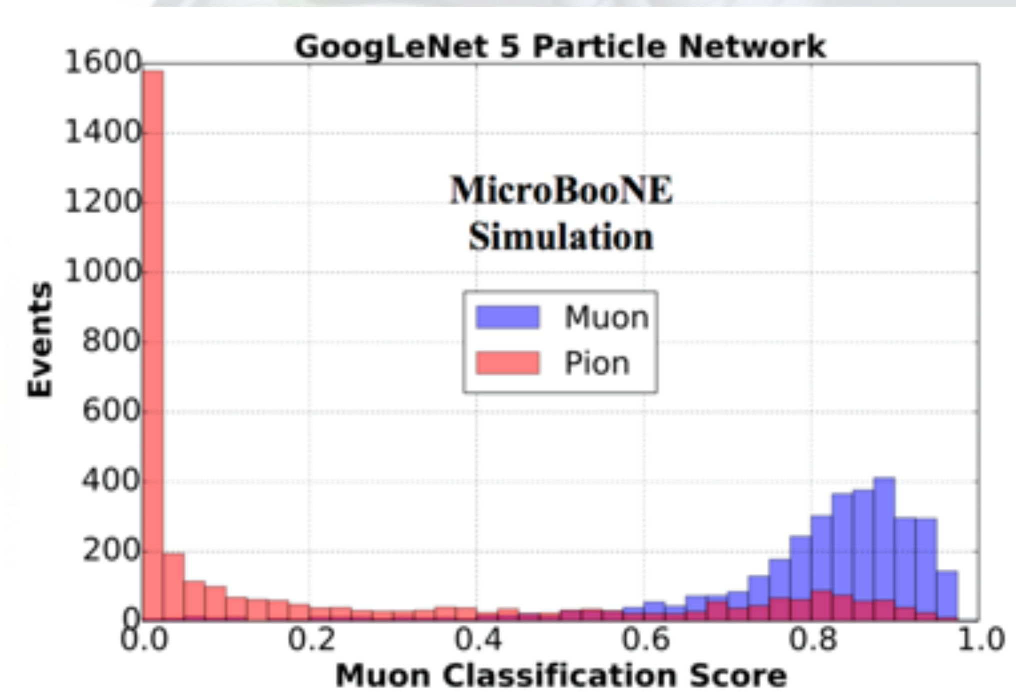
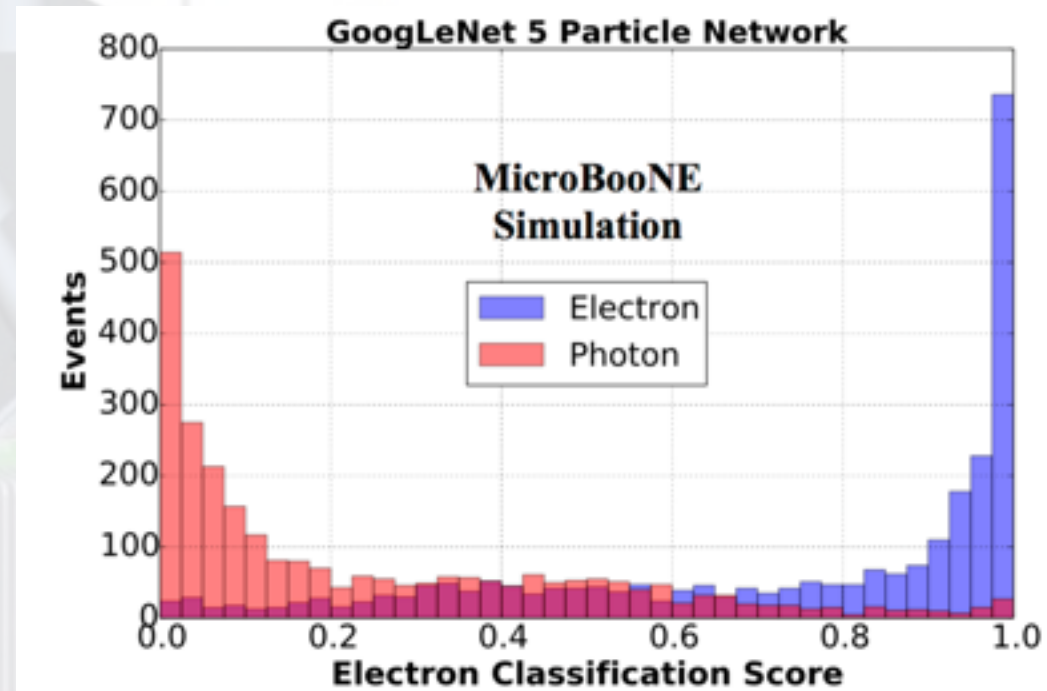
MicroBooNE ν Physics

Exploring different options to select our neutrinos





First MicroBooNE publication:

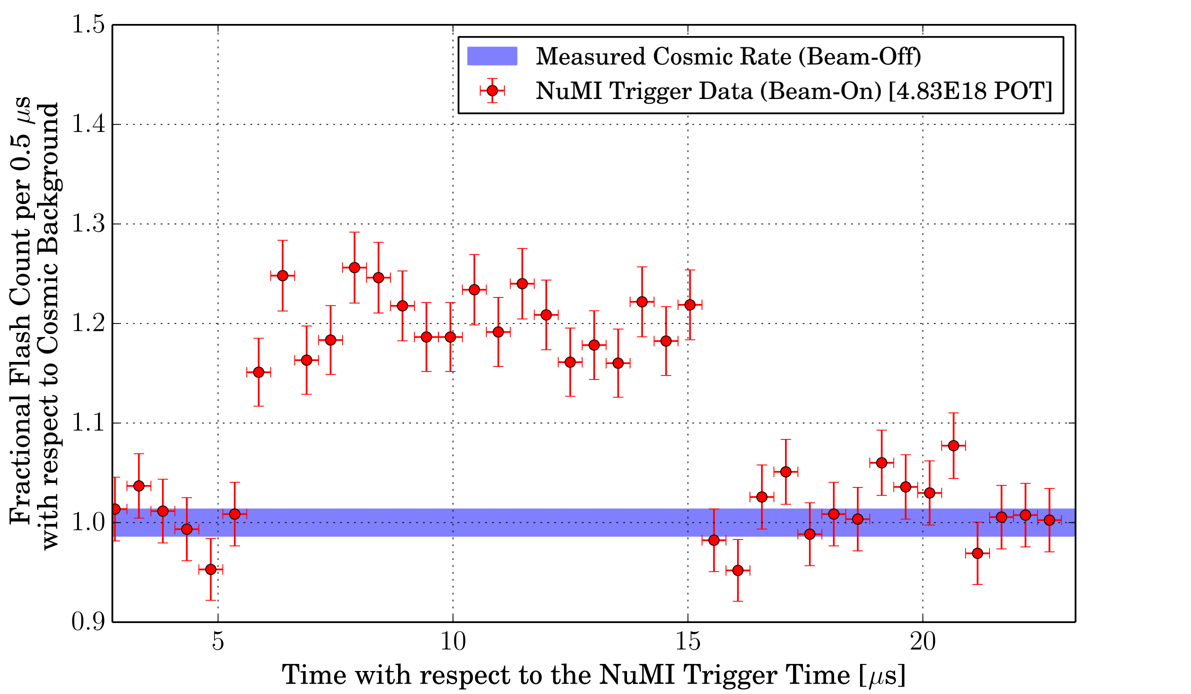
Convolutional Neural Networks Applied to Neutrino Events in a Liquid Argon Time Projection Chamber, arXiv:1611.05531

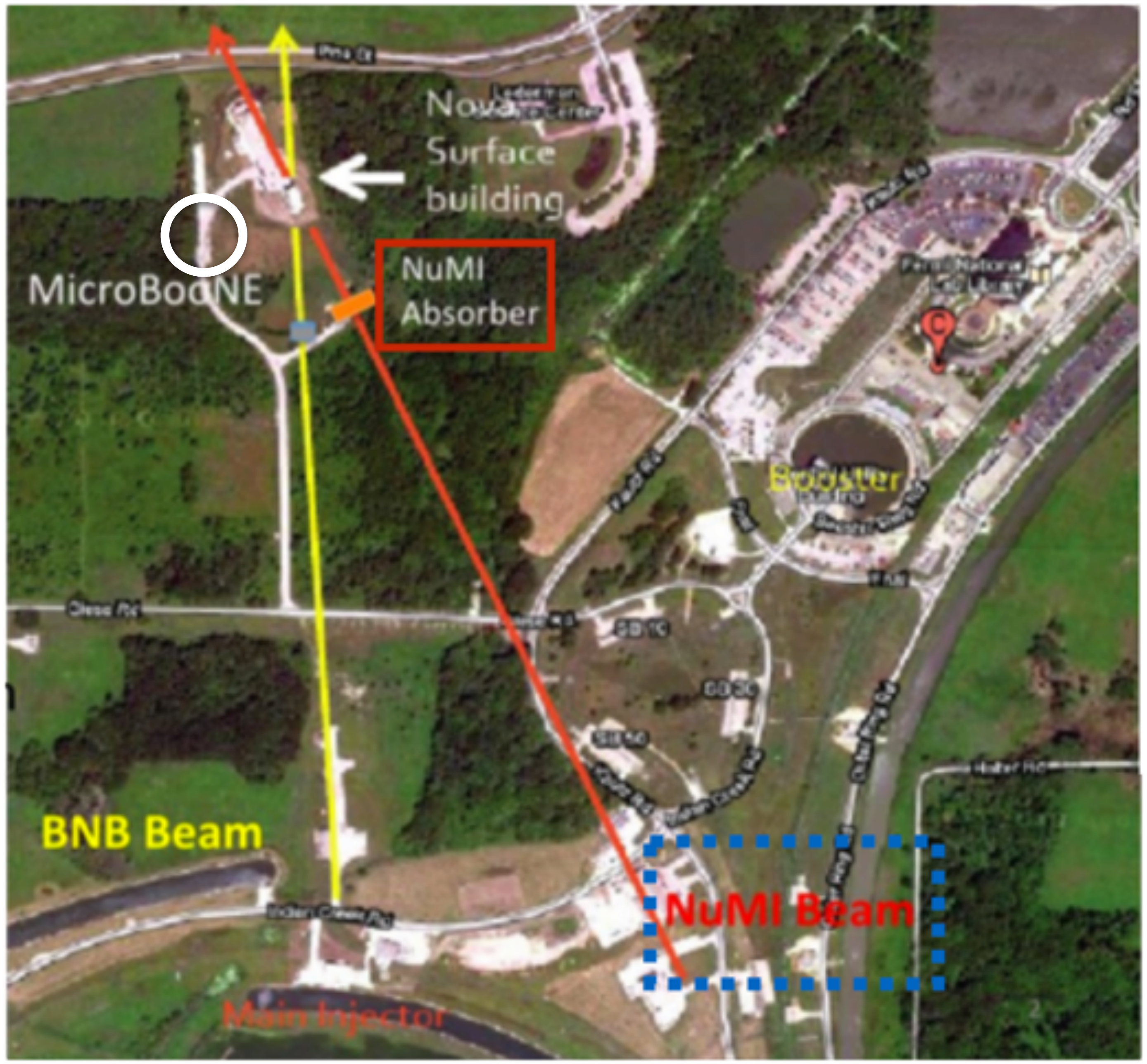
Using Deep Learning techniques to identify ν events from cosmics

- The ν Oscillation Phenomenon
  - ν Energy Reconstruction
  - ν Interactions
- ν ‘anomalies’
- Precision era: LArTPC
- The SBN Program
  - The MicroBooNE Detector
  - MicroBooNE ν Physics
    - **MicroBooNE NuMI ν’s**

MicroBooNE ν Physics

NuMI: On the way to constrain ν-Argon interactions



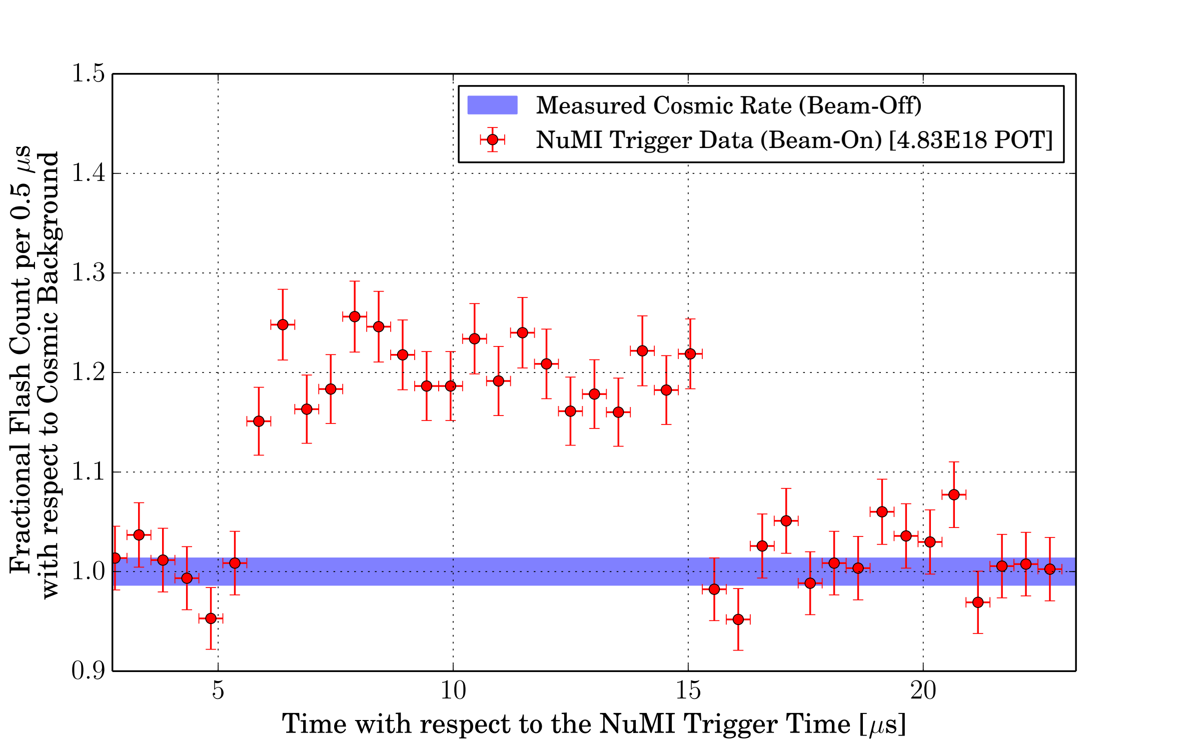


MicroBooNE receives 2 different neutrino beams: BNB but also NuMI
NuMI arrives off-axis ~6 degrees wrt z

Double the beam, double the fun!

MicroBooNE ν Physics

NuMI: On the way to constrain ν-Argon interactions



Ongoing studies on <u>ν_e CC inclusive</u> cross section.

- Fundamental to understand the ν_e spectrum in a non-oscillation hypothesis

Ongoing different studies in ν_μ events.

- Fundamental to have a first comprehension of <u>ν-Ar interactions and their uncertainties</u>
- Understand <u>ν_e / ν_μ</u>

Fundamental to understand if any possible anomaly in the BNB induced neutrino interactions are due to:

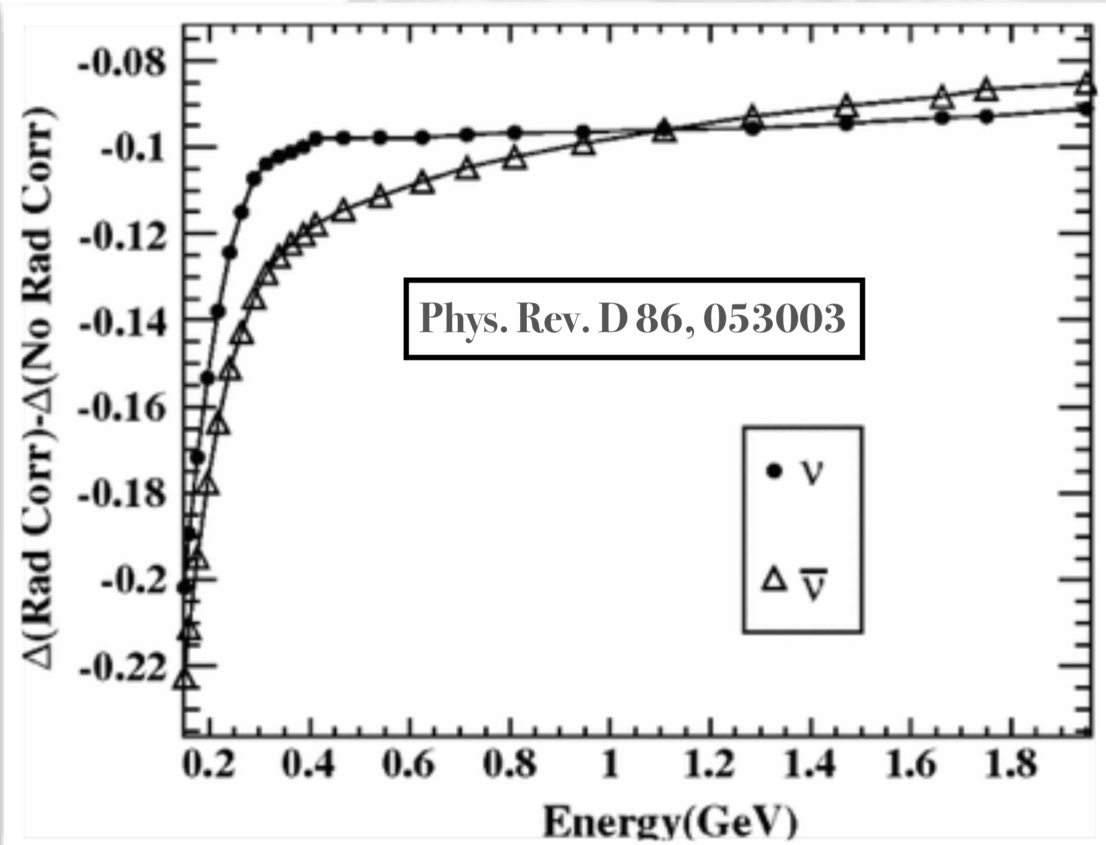
- lepton differences
- cross section unknowns

NuMI has been producing neutrino data for MicroBooNE during 1.5 year and now it is producing anti-neutrino data.

- This will allow us to start studies ν/anti-ν

MicroBooNE ν Physics

NuMI: On the way to constrain ν-Argon interactions



Ongoing studies on ν_e CC inclusive cross section.

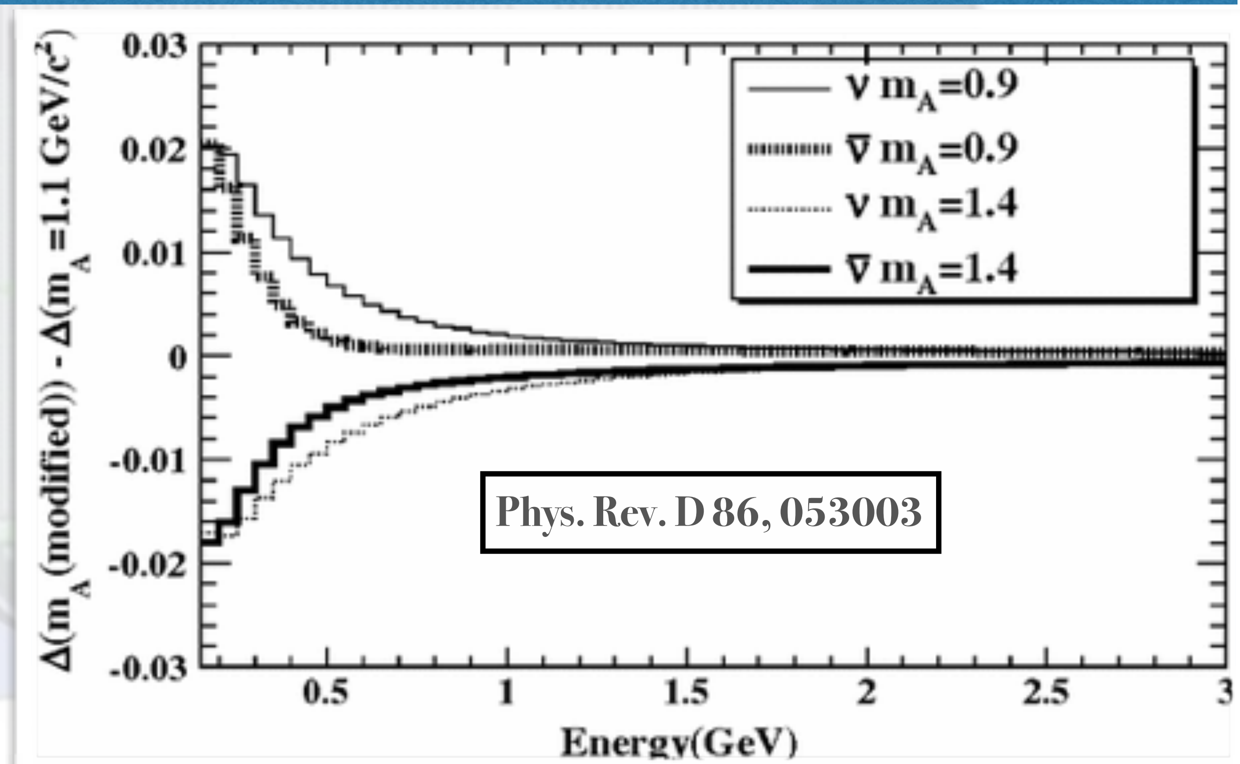
- Fundamental to understand the ν_e spectrum in a non-oscillation hypothesis

Ongoing different studies in ν_μ events.

- Fundamental to have a first comprehension of ν-Ar interactions and their uncertainties
- Understand ν_e / ν_μ

Calculations shows differences in ν_e / ν_μ induced by:

- form factors
- radiative corrections
- lepton mass

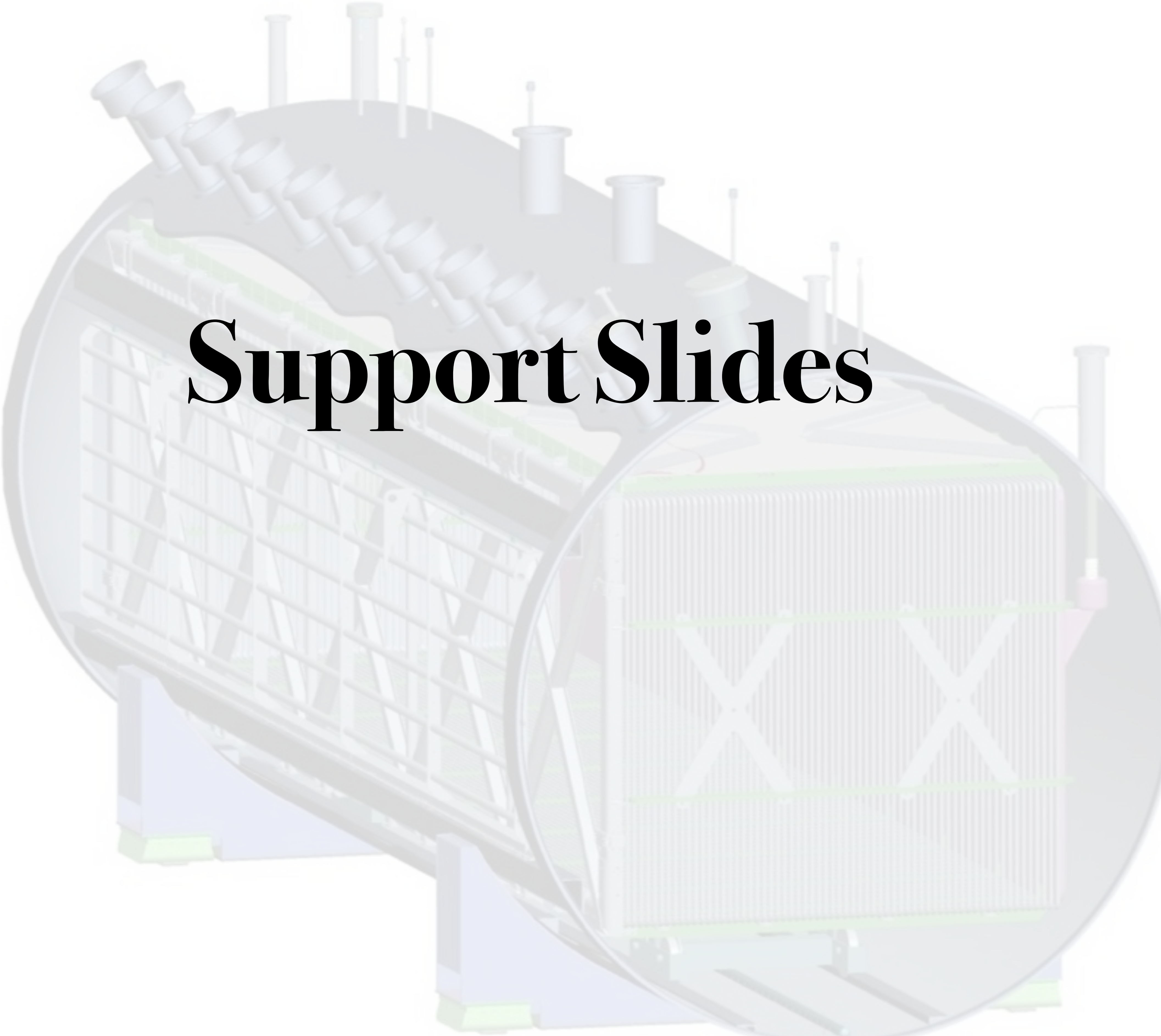


Conclusions

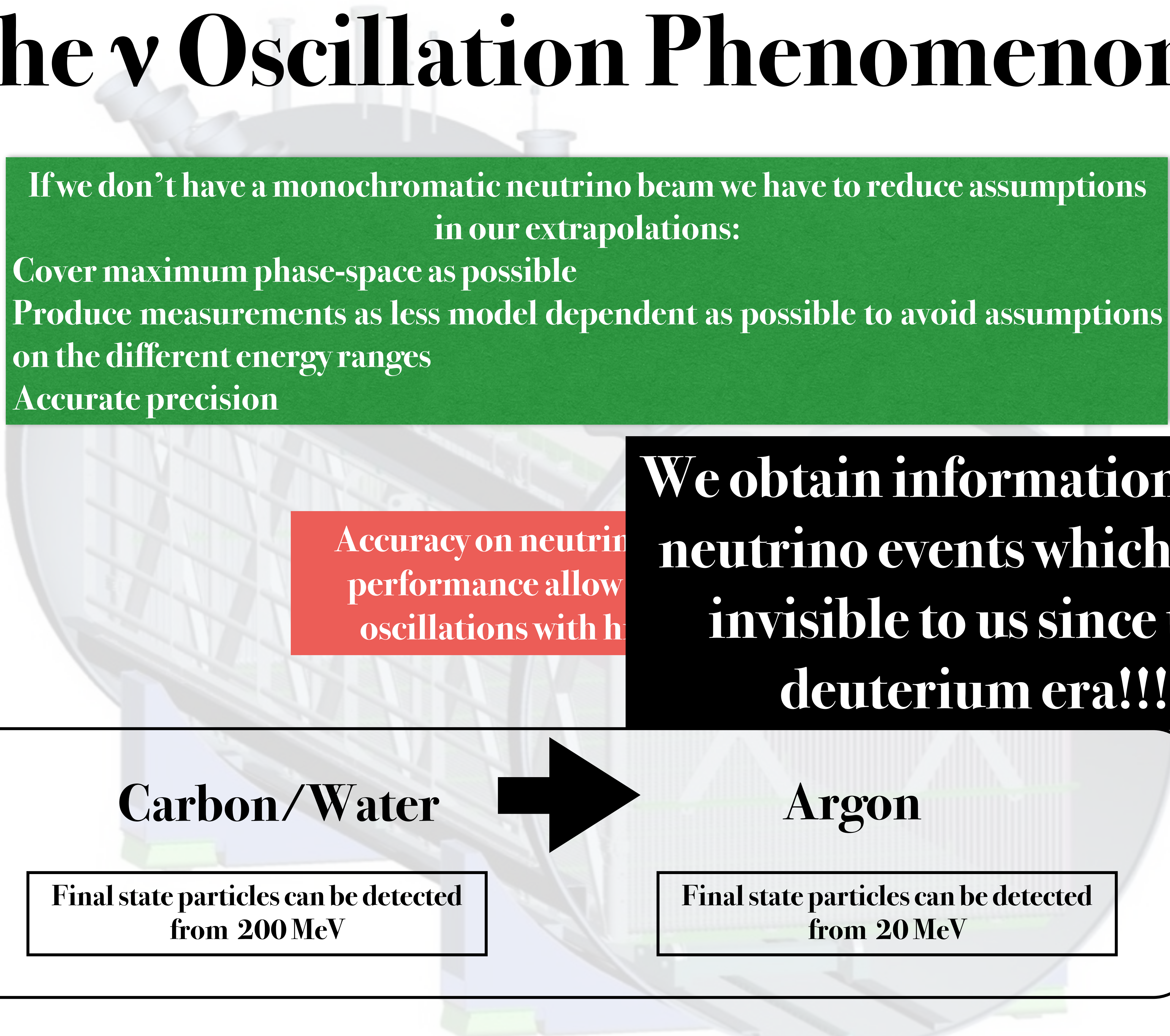
- Exploring anomalies seen by other experiments. Different possible explanations:
  - ν cross section mis-modeling/uncertainties (π background unknowns, lepton differences, nuclear effects)
  - Non-Standard Physics (e.g. sterile and heavy neutrinos)
- LArTPC detectors can achieve unprecedented precision in:
  - e/γ separation
  - Biggest phase-space covered since deuterium experiments
- MicroBooNE is taking neutrino data since more than 1 year. First large LArTPC operating with front end cold electronics
- Ongoing a huge effort to characterize the detector. Developing new tools for track and shower 3D reconstruction
- Working on produce first ν-Ar cross sections at low energies
- Taking data with 2 different ν beams
- Part of the SBN program

Lot of physics to come!!!

Support Slides



The ν Oscillation Phenomenon



If we don't have a monochromatic neutrino beam we have to reduce assumptions in our extrapolations:

Cover maximum phase-space as possible

Produce measurements as less model dependent as possible to avoid assumptions on the different energy ranges

Accurate precision

Accuracy on neutrin
performance allow
oscillations with h

We obtain information from neutrino events which were invisible to us since the deuterium era!!!

Carbon/Water → **Argon**

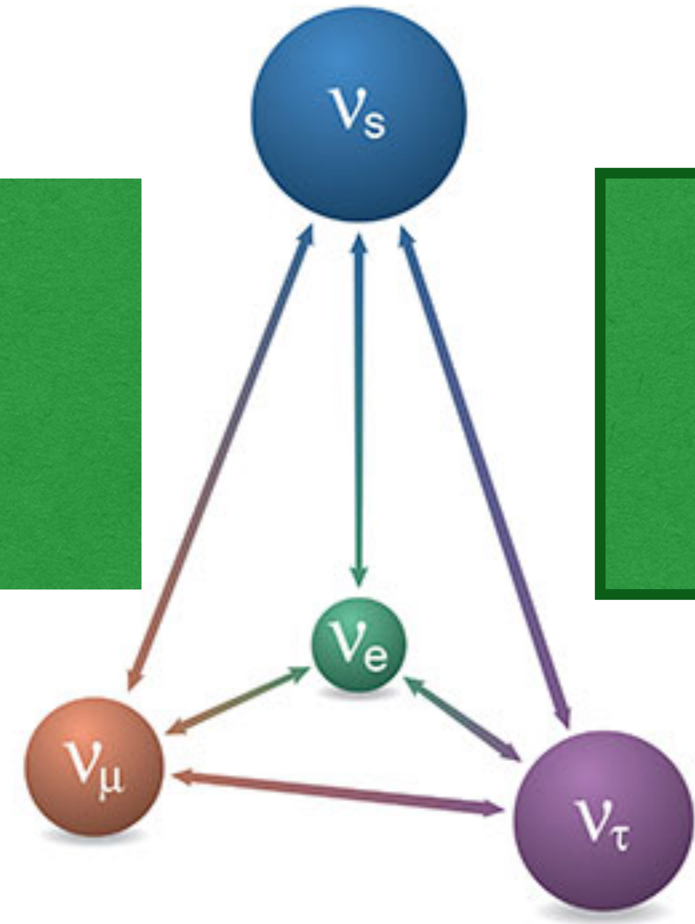
Final state particles can be detected from 200 MeV

Final state particles can be detected from 20 MeV

Why do we look for sterile ν?

Regular Standar Model ν:

massive (spin -1/2) particles
no electric or color charge
Affected by electroweak force



Sterile ν:

massive (spin -1/2) particles
no electric or color charge
Not affected by any force

- They can, in principle, be their own anti-particle ('sterile Majorama ν').
- Since they are not associated with either the strong nuclear or electroweak symmetry breaking scales, in principle they can have an arbitrary large/small mass!!
- Since they do have mass and at low energies they act like regular Standard Model Neutrinos, they can participate in neutrino flavor oscillations.

MicroBooNE ν Physics

First efforts on the ν_μ CC selection for the BNB events

Selection I

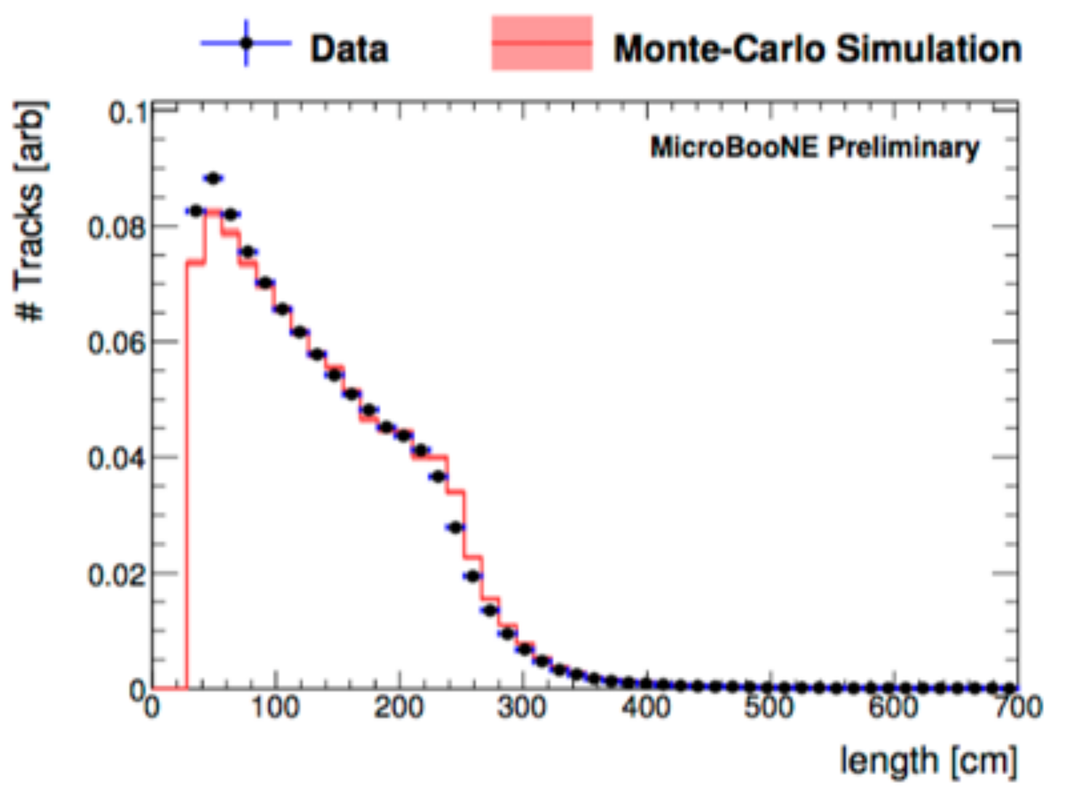
- Longest track fully contained (μ candidate)
- Start position μ candidate in FV
- Candidate μ start position-tracks within 3cm
- Track and flash must be matched in z
- Candidate μ length > 75 cm

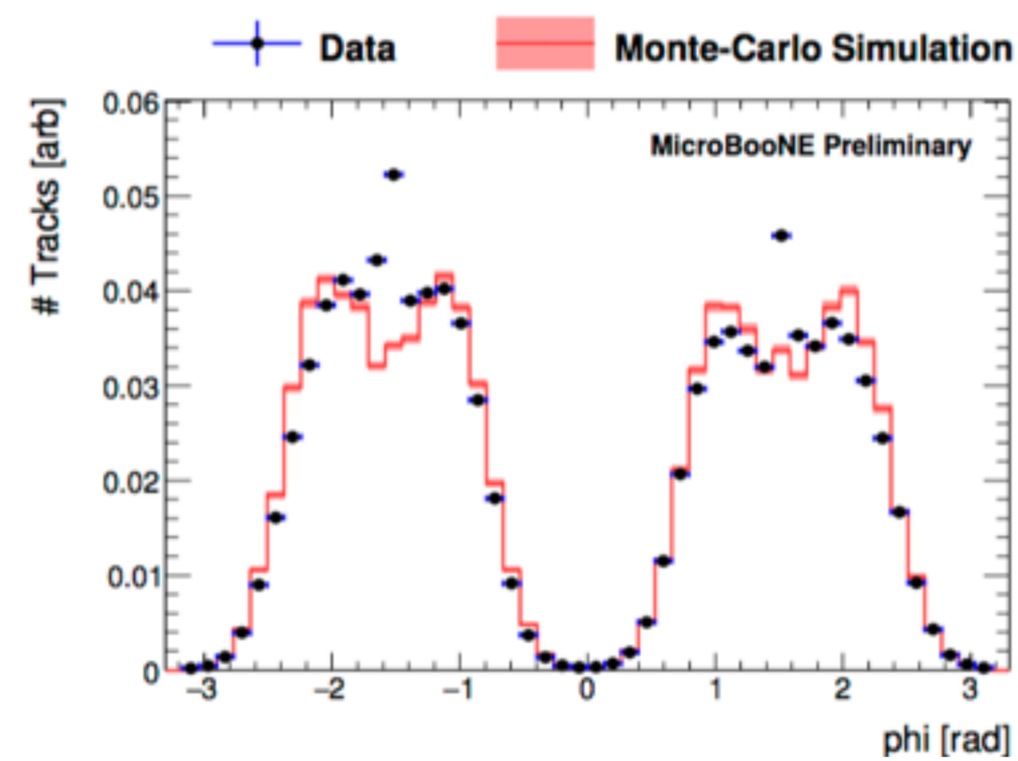
Selection II

- If only 1 track: fully contained (μ candidate)
    - Otherwise, longest track is the μ candidate
- Start position μ candidate in FV
- Candidate μ start position-tracks within 3cm
- Track and flash must be matched in z
- If only 1 track:
    - candidate μ length > 40 cm
- If > 1 track,
    - min. length any other track > 15 cm
    - Michel removal

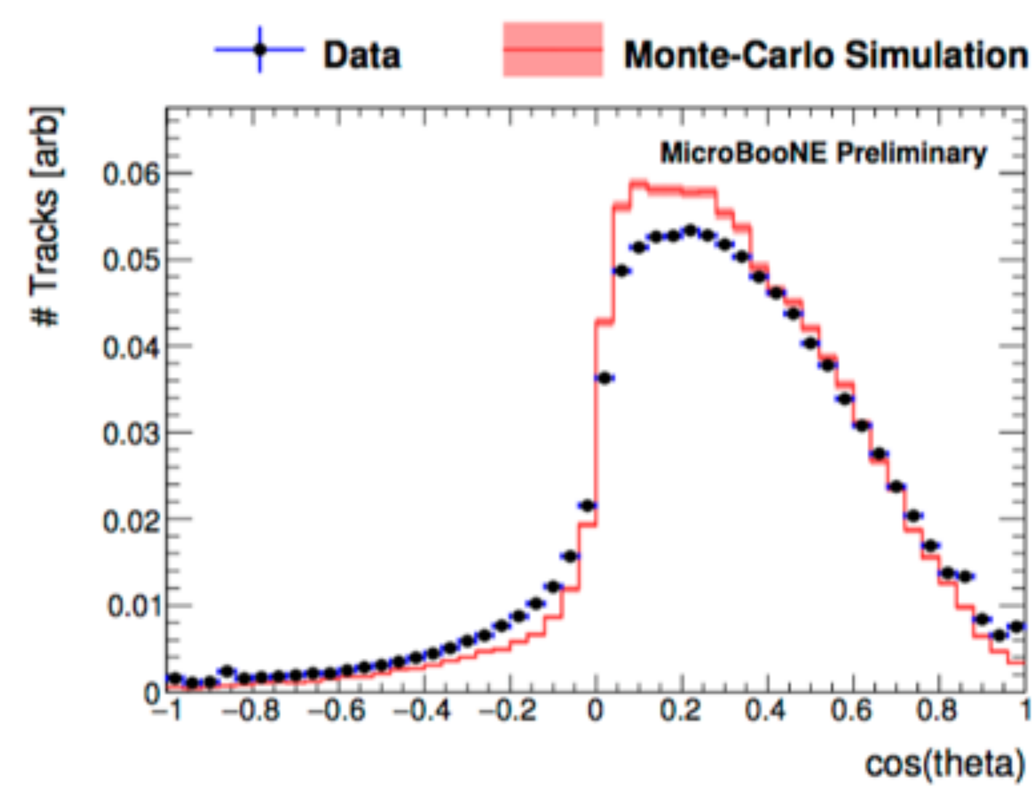
MicroBooNE ν Physics

We combine hit information from the 3 planes to reconstruct 3D objects





Area normalized



Data/MC comparison for neutrino& cosmic events